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CARBONATE DIKES OF THE PREMIER DIAMOND MINE, TRANSVAAL

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ABSTRACT

The kimberlite of the Premier Mine is cut by a considerable number of dikes, which are essentially composed of calcium carbonate, magnesium hydrate, and magnesium carbonate, the last being in variable, but always small, amount. The dominant carbonate appears to be of direct magmatic origin.

At depth, the Premier Mine kimberlite cuts the Great Dolomite, here about 1,000 meters thick. The suggestion is offered that the carbonate magma was generated by the dissociation of the dolomite, which was locally heated through deep burial and the eruption of the kimberlite.

Experiments on the existing dike material, by Dr. F. H. Smyth, show its fusion temperature to be below 950° C. The temperature of the carbonate melt was probably well below 900°. Dr. Smyth finds that the magnesium hydrate and magnesium carbonate could not have been formed at a temperature which approached 900°. Hence it is necessary to assume the late-magmatic or post-magmatic generation of these compounds. On the other hand, the hypothesis that the dominant calcium carbonate was introduced in dilute, low-temperature solution with water does not square with clear facts discovered during the field and laboratory investigation.

INTRODUCTION

During the year 1922 the writer, as a member of a Shaler Memorial Expedition from Harvard University, was privileged to spend two days in petrological study at the great volcanic vent of the Premier Mine of the Transvaal. Among the features of its extraordinary geology is the existence of tabular masses of carbonate-rich

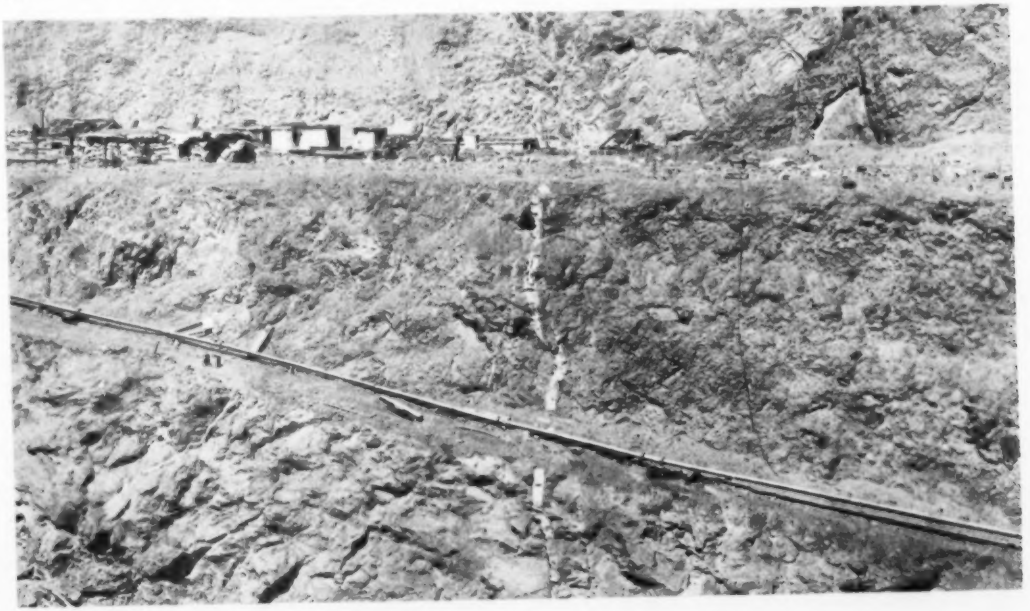
rock, which cut the famous blue ground (kimberlite), and also bodies of Waterberg sandstone and conglomerate, included in the blue ground. The carbonate rocks have the field habit of dikes, essentially unaltered (Plates V–VIII). Hence special attention was devoted to their mapping and sampling, in order to test the field impression by laboratory study. This paper contains the conclusion that the bodies of carbonate rock are probably genuine intrusive dikes and of magmatic origin, the magmatic solution having been derived from highly heated and somewhat dissociated dolomite in depth, to which water, serpentine, and iron oxide from the blue ground were added.

During the field work the writer was much aided by his colleague, Professor Charles Palache, another member of the expedition. The laboratory study was furthered by the interest and skill of Dr. F. H. Smyth, of the Geophysical Laboratory at Washington, and of Professor E. S. Larsen, at Harvard University. For all this generous help the writer's thanks are due, and also for permission to enter the mine, kindly given by Mr. D. McHardy, manager for the Premier Diamond Mining Company.

WAGNER'S DESCRIPTION OF THE DIKES

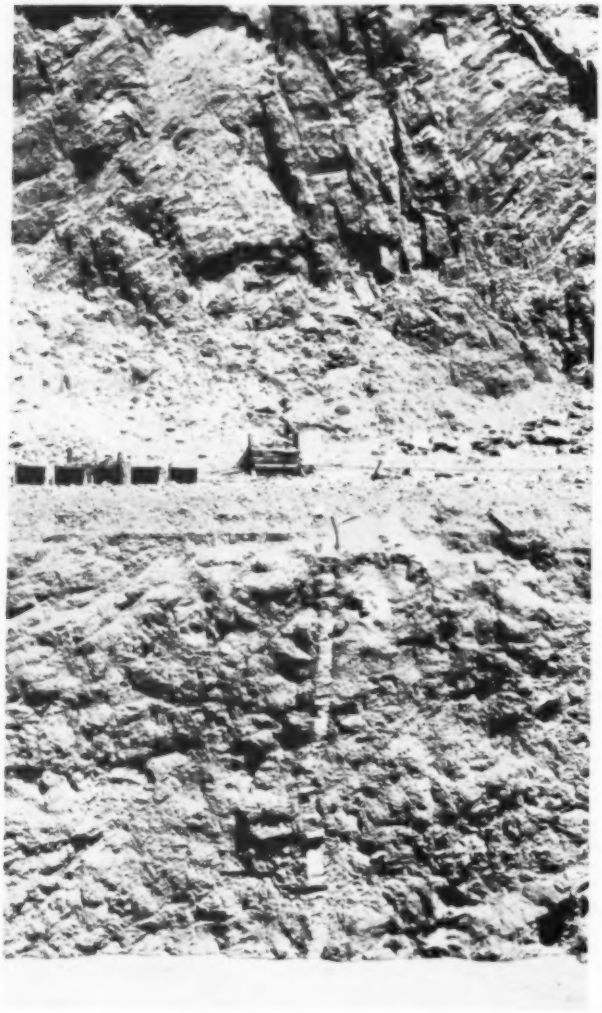
P. A. Wagner's masterly volume, *The Diamond Fields of Southern Africa* (Johannesburg, 1914), contains the first detailed account of the "calciferous dikes" of the Premier Mine. He writes (pp. 98–100):

> Intersecting the blue ground one finds, in addition to at least one normal kimberlite intrusion, numerous dikes or veins of a remarkable calciferous rock. These generally take the form of wall-like bodies, varying in width from a few inches to 6 feet, but in the northern portion of the mine there is a large, irregularly lenticular mass of the same rock, over 60 feet in width, from which some of the smaller dikes are seen to emanate. The latter are themselves as a rule somewhat lenticular in character; and not infrequently a dike of this type may be seen to pinch out altogether, and to be replaced at some little distance to one side by an apparently distinct intrusion. The dikes are always sharply defined from the blue ground, and generally cut up by transverse joints into polygonal columns or rectangular blocks.
>
> The normal dike material is a compact black rock, which effervesces violently on being moistened with acids. Under the microscope it is seen to be made up almost entirely of calcite, containing some 10 per cent of magnesium



CARBONATE DIKES CUTTING BLUE GROUND

The interrupted dike in the middle of the picture is the 30-cm. dike of Fig. 2. On the left, below the pipe, may be seen the 10-cm. dike.



THE 28-CM. CARBONATE DIKE CUTTING BLUE GROUND ABOVE A POND AT THE BOTTOM OF THE MINE.

GENERAL VIEW OF THE 58-CM. DIKE CUTTING BLUE GROUND

VIEW OF THE 58-CM. DIKE, SHOWING CONTACT-SHELLS OF DARK-COLORED COMPACT SERPENTINE

carbonate and of crystals and granules of magnetite, these minerals being accompanied by occasional patches of serpentine. Magnetite is so abundant as to render the rock distinctly magnetic. The character of the dike rock is thus most peculiar, and a superficial examination of thin sections leaves one in serious doubt as to its true nature. Upon closer investigation, however, the writer was led to conclude, from the mode of occurrence of the carbonate matter in large clear areas, some of which enclose remnants of serpentine, and from the disposition of the granules of magnetite around these, that we are dealing with an extreme form of alteration of a porphyritic igneous rock, resembling kimberlite in structure. This view receives indorsement from the petrographical character of the superficial portions of the dikes, in the vicinity of their original outcrops. Here the carbonate matter has been removed by leaching, and in place of the dense black material one sees a somewhat porous rock of reddish-brown color, through which are scattered small patches of a dirty green material. The microscope reveals pseudomorphs of serpentine after olivine, set in a ground mass of finely fibrous serpentine, which is again crowded with grains of magnetite, largely altered to hematite. To the presence of the latter mineral the rock owes its peculiar color. The blue ground in contact with, and in the vicinity of, the large lenticular body of this calciferous rock has been completely saturated with calcite and converted into "harde-bank." The dikes are accompanied by similar impregnation zones, though these, by reason of their more limited extent, are less noticeable.

Two important problems arise in connection with the dikes under discussion. These relate to the original character of the dike rock, and to the source of the calcite with which the latter is so strongly impregnated. With regard to the former of these problems, we can only reiterate that the unaltered dike material appears to have been a porphyritic igneous rock, resembling kimberlite in structure. As to its original composition, we have no data to go upon. The existence of such large quantities of calcite in, and in the vicinity of, these intrusions is likewise a matter of some obscurity; more particularly since this mineral is by no means abundant in the blue ground of the Premier Mine. It may possibly owe its presence to hydrothermal action, representing a final phase of the volcanic outbursts. The dikes themselves were presumably formed by the injection of residual portions of the kimberlite magna into fissures opened up in the material filling the vent; and it is conceivable that these same lines of weakness may subsequently have afforded a ready passage for the circulation of heated magmatic waters, containing calcium carbonate in solution. This, at any rate, is a point upon which the progressive deepening of the mine workings should throw much light.

The present writer has not been able to find any other publication dealing with the subject. Since 1914 some of the dike material studied by Wagner has been quarried away, and new dikes have been exposed. Yet Wagner's description permits no doubt of the

full similarity of the material exposed in 1922 with that seen at higher levels of the colossal excavation. Before proceeding with the account of the new data, a glance at the general geology of the region may profitably be taken.

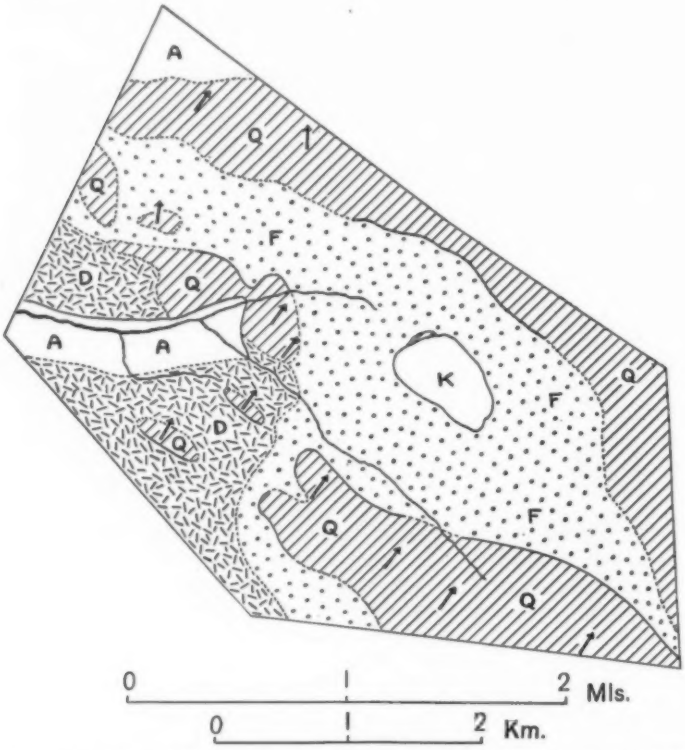


FIG. 1.—Copy of H. Kynaston's geological map of Premier mine and vicinity (*Ann. Rep. Geol. Surv. Transvaal for 1903*, Plate 23). *K*, kimberlite of mine; *F*, felsite; *D*, diabase; *Q*, quartzite of the Pretoria series; *A*, alluvium. Arrows indicate dips.

GEOLOGY OF THE DISTRICT

Figure 1 is a copy of a map of the farm Elandsfontein No. 85, by Kynaston (Plate XXIII, "Annual Report for 1903," *Geological Survey of the Transvaal*). In the accompanying text, by H. Kynaston

and A. L. Hall, is found a convenient explanation of the map and of the geological structure (pp. 43, 45):

> The Premier diamond pipe . . . . has an elevated situation compared with the general level of most of the surrounding country, and lies in a basin-shaped hollow, encircled by ridges and *kopjes* of felsite.
>
> At the surface the outline of the pipe forms an irregular oval, the longer diameter of which measures just over half a mile. . . . . The Premier pipe is, therefore, the largest known diamondiferous vent in the world. . . . .
>
> The pipe is almost entirely surrounded by felsitic rocks, which, as already pointed out (see p. 5 of this report), constitute the upper portion of an extensive sheet intrusive in quartzites of the Pretoria series. In addition to the felsite, a small patch of quartzite is found cropping out on the northern edge of the pipe.
>
> There is no reason, however, to suppose that the felsite has any connection whatever with the volcanic forces to which the pipe owes its origin. It was undoubtedly intruded into the Pretoria beds at a time far anterior to the formation of the pipe, which has, at a much later date, been pierced through the felsite and the quartzites which underlie it. Thus the walls of the pipe, where they are exposed in the present open workings (No. 1), are composed of this felsite. At greater depths, however, the walls would in all probability be found to be composed of the quartzites, which the structure of the surrounding country shows to underlie the felsite.

After describing the nature of the blue ground and the occurrence of large masses of "floating reef" (Waterberg conglomerate and sandstone) in it, the authors proceed:

> It would not be unreasonable, therefore, to conclude that the Pretoria beds, which at present surround the pipe, were at one time covered by conglomerates and sandstones of Waterberg age, and that the masses of these latter rocks, now found enclosed in the diamondiferous ground, represent portions which had been broken away from the sides of the old volcanic crater which stood over the site of the present pipe, and in this way became buried in the volcanic matter within it. Since that time the volcanic crater and the surrounding Waterberg rocks have been swept away by denudation, so that today we see the pipe or vent which fed this ancient volcano surrounded by the underlying Pretoria quartzites and intrusive igneous rocks.

On pages 21–22 of his book Wagner gives a brief description of the "floating reef":

> Running right across the Premier Mine . . . . is a great bar made up of red quartzite, conglomerate, and sandstone, which clearly belong to the Waterberg formation, now completely stripped by erosion from the area surrounding the mine; the closest occurrence *in situ* being a small outlier, exposed some three miles to the north, on the farm Louwsbaken 309. This great mass of rock, which

dips at a steep angle to the north, has been followed down to the 260-feet level and extends to an unknown depth. It divides the mine into two distinct sections; and it is quite possible that during the final phases of the volcanic activity it may have played some rôle in establishing two separate craters. Smaller xenoliths of Waterberg quartzite are very common in the southeastern and south-central portions of the mine, and also in the blue ground adjoining the northwestern wall.

In Figure 2 the present writer offers a rough sketch of the main body of the Waterberg rocks in the pipe, and also indicates the posi-

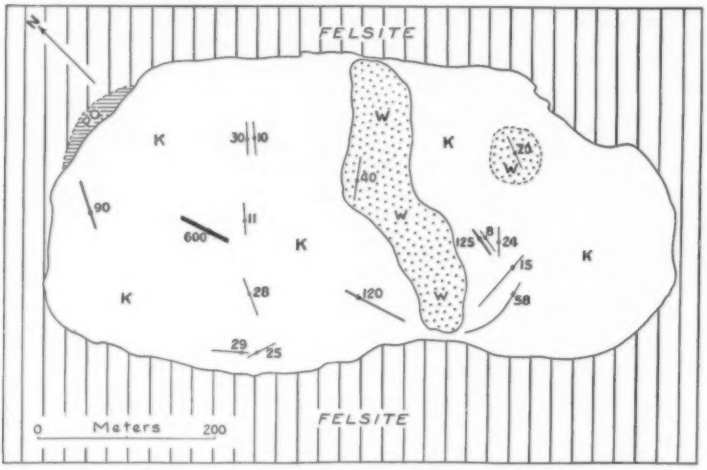


FIG. 2.—Sketch map of the Premier mine, showing kimberlite, *K*, inclosing large masses of Waterberg sandstone-conglomerate, *W*. *PQ*, quartzite of the Pretoria series. Carbonate dikes shown by lines; numbers represent their maximum widths in centimeters.

tion of a much smaller body, to the southeastward, which is also tentatively referred to the Waterberg. This map is not quite accurate, since the boundary of the blue ground (*K*) was taken as coincident with the break of slope at the edge of the excavation. However, the contact of blue ground and felsite is so nearly vertical, down to the greatest depths at which it has been exposed by mining, that for the purpose of the sketch the error is not important. The patch of Pretoria quartzite shown at the north end of the pipe has been mapped as in Kynaston's original paper.

The diabase, mapped in Figure 1, passes upward into a medium-grained to fine-grained granophyric rock, which is locally roofed by Pretoria quartzite. Kynaston indicated this more salic rock as continuous with the dense felsite surrounding the mine. He regarded all three rocks as phases of a single intrusive mass, which was injected "not far below the junction of the Pretoria and Waterberg Systems."[1] Yet fragments of the felsite were found in the Waterberg conglomerate at the mine, and it seems fairly clear that the felsite was erupted before the Waterberg strata were deposited. Such is the case with the lithologically very similar felsite of the Bushveld Igneous Complex, of which the felsite-diabase body at the Premier Mine is probably an offshoot.[2]

Incidentally, doubt may be expressed that the felsite at the mine is to be fairly described as intrusive. If the Waterberg system did not exist at the time of the eruption, this felsite could hardly have had any sedimentary roof, unless one postulates a post-Pretoria and pre-Waterberg stratified series. No such rocks are known in the Transvaal. Moreover, the grain of the felsite is not that expected in an intrusive. No facts have come to light which forbid belief that the Premier felsite is extrusive, though in depth it may be transitional into diabase with local intrusive relations.

The oldest fossiliferous beds of the Transvaal belong to the Karroo system, whose basal Dwyka is now referred to the Carboniferous. The Karroo lies in pronounced unconformity on the Waterberg system, which in turn is unconformable on the Pretoria series, the uppermost part of the thick Transvaal system. The Waterberg beds are generally regarded as pre-Devonian. On that assumption the eruption of the Premier Mine felsite must be dated in pre-Devonian time. With Du Toit and other South African geologists, Wagner believes the date of the eruption of the blue-ground kimberlite to be probably best placed in the late Cretaceous. Thus the relevant facts discovered during the last twenty years tend to corroborate the conclusion of Kynaston and Hall as to the great length of time elapsing between the eruption of the felsite and the eruption of the kimberlite. Any direct thermal or chemical connection be-

[1] H. Kynaston, Explanation of Sheet No. 1, *Geol. Survey Transvaal* (Pretoria, 1907), p. 20.

[2] Cf. R. A. Daly and G. A. F. Molengraaff, *Jour. Geol.*, Vol. XXXII (1924), p. 1.

tween the two magmas must be regarded as highly improbable.

The dikes of calciferous rock are obviously younger than the kimberlite. How much younger cannot be shown, but it is difficult to resist Wagner's conclusion, that the dikes and the kimberlite belong to the same petrogenic period or cycle.

Another relation of the Premier pipe, of special significance for the present problem, merits attention. The pre-Waterberg quartzites outcropping at and around the Premier Mine have been mapped by the government survey as belonging to the Daspoort member of the Pretoria series, though certain large outcrops may be referable to the Magaliesberg quartzite, the youngest member of the series. Beneath the Daspoort quartzite is a very thick series of shales, interrupted by the Timeball Hill quartzite. The lowest shales rest on the Campbell Rand or Great Dolomite, which is of the order of 1,000 meters in thickness. The conformably underlying, thin Black Reef quartzite is the base of the Transvaal system, and probably here, as it certainly does south of Pretoria, rests in major unconformity on the massive gneiss and granite of the crystalline basement of the Transvaal. Thus the Premier volcanic pipe passes through thick shales and thick dolomite as well as quartzite, all far below the present surface. How far below is a question not easy to decide, but the respective depths are likely to be considerably greater than those estimated directly from measured sections of the Transvaal system, because the Transvaal beds of the region are split by a number of thick sills of "diabase." It is possible that the top of the Great Dolomite, for example, is as much as five kilometers below the present surface, and it may be much deeper. The sills, contemporaneous with the diabase shown in Figure 1, were intruded long before the Premier pipe was formed.

Further evidence that the Great Dolomite was traversed by the kimberlite magma is found in the discovery of many fragments of metamorphosed dolomite in the volcanic breccia now being quarried.

The stratigraphy of the region may conveniently be reviewed in a table of formations, listed from youngest to oldest:

Late Cretaceous (?)	Carbonate dikes
	Kimberlite: massive phase, tuff, breccias, dikes
	Long interval of time

Carboniferous to Triassic	Karroo beds (not represented at the mine)
	Unconformity
Pre-Devonian	Waterberg system, conglomerates, and sandstones
	Long interval of time
Pre-Devonian	Eruption of felsite-diabase body and of many diabase sills (probably offshoots of the Bushveld Igneous Complex)
Pre-Cambrian (?)	Transvaal system (unconformable below the Waterberg)—subdivisions:
	Pretoria series
	Magaliesberg quartzite
	Shales
	Daspoort quartzite
	Shales
	Timeball Hill quartzite
	Shales
	Great Dolomite
	Black Reef quartzite
	Unconformity
Old Pre-Cambrian	Granite and gneiss of crystalline basement

THE PIPE ROCK

In Wagner's book will be found an excellent description of the blue-ground and harde-bank phases of the rock constituting the younger volcanic mass. Its dominant constituent is serpentine, in which crystals and grains of olivine, phlogopite, enstatite, diallage, diopside, hornblende, pyrope, ilmenite, chromite, picotite, titanite, zircon, perovskite, magnetite, apatite, rutile, diamond, calcite, chlorite, opal, etc. are imbedded. Many of these minerals occur as individuals and also in the form of cognate xenoliths. As in nearly all of the South African diamondiferous pipes, the kimberlite was extraordinarily explosive, so that the material is largely pyroclastic. The breccia is cut by occasional narrow dikes of kimberlite, in which, too, serpentine is the chief constituent.

Three typical analyses of the blue ground, quoted from Wagner's book (p. 98), are given in columns 1, 2, and 3 of Table I.

Nearly all authorities have attributed the high content of water to serpentinization of a peridotite which was originally poor in volatile constituents. Most writers, including Wagner, believe the alteration to have been due to the action of surface water. Yet the

tremendous explosions that took place at the Premier, Kimberley, and other pipes prove the original magma to have been charged with gas to an unusual degree, and the simplest supposition is that the high tension was connected with the presence of magmatic water in quantity sufficient for the crystallization of magmatic serpentine. On this view the subordinate olivine, phlogopite, etc. are regarded as also primary, though one of the conditions for the crystallization of olivine may have been the local loss of water from the magma during the successive explosions.

TABLE I

TYPICAL ANALYSES OF BLUE GROUND

Constituent	1	2	3	4*
SiO_2	38.29	38.02	38.15	38.15
TiO_2	2.00	2.30	1.72	2.01
Al_2O_3	2.66	3.03	1.19	2.29
Fe_2O_3	5.77	8.13	6.55	6.82
FeO	2.93	2.21	3.24	2.79
MgO	29.46	27.78	27.33	28.19
CaO	2.42	4.80	4.13	3.78
Na_2O	0.30	0.84	0.25	0.27
K_2O	1.03		0.56	0.74
H_2O-	3.13	2.60	3.52	3.08
H_2O+	10.19	10.11	9.69	10.00
CO_2	0.20	0.28	1.41	0.63
P_2O_5	1.44	0.41	2.15	1.33
Totals	99.82	100.51	99.89	100.08
Specific gravity	2.68	2.695	2.64	2.67

* Simple average of preceding columns.

A proper discussion of the difficult problem of kimberlite cannot here be undertaken. It may merely be pointed out that the foregoing speculation is in line with the conclusion of several special students of massive serpentine who explain its formation by magmatic processes rather than by weathering. For the present problem the matter is of some practical importance, since the emplacement and character of the carbonate dikes seem to have been somewhat controlled by the amount of water then resident in the blue ground.

THE CARBONATE DIKES

The first quotation from Wagner's book gives a general account of the calciferous dikes. Figure 2 shows their distribution on the

floor of the pit in February, 1922. Lack of time forbade very accurate mapping, but the distribution shown on the map is in principle correct. The numbers attached to the (duly orientated) dikes represent the widths of the dikes in centimeters. The 30-centimeter and 11-centimeter dikes may be continuous under the débris of the pit floor. As Wagner noted, the dikes tend to be lenticular and broken by offsets (Plate V). Two dikes cut the quartzitic sandstone or conglomerate of the "floating" Waterberg. All the others cut the blue ground. None was seen to cut the felsite of the walls of the pit or to cut another carbonate dike. The dikes themselves are commonly jointed (see Wagner's Figure 27 and Plate VIII of this paper). Here and there thin veins of white or slightly yellowish clear calcite have been deposited in the joints. No igneous dike cuts any of the carbonate dikes.

Without exception the dikes, generally vertical or nearly so, appear sharply marked off from the country rock. On closer inspection of the dikes cutting the blue ground, the contacts are seen to be thoroughly welded. To a depth of 1 to 5 centimeters from each of these contacts the friable, more or less variegated, material of the blue ground has been altered into a much stronger, deep gray-green, homogeneous serpentine, which passes rapidly into the normal blue ground on each side of the dike (Plate VIII). The thickness of the contact-shells tends to vary directly with the widths of the dikes.

No such contact-shells of compact serpentine characterize the dikes cutting the silicious Waterberg rocks. This contrast at once suggests that the shells are due to the contact metamorphism of the blue ground.

Most of the dikes cutting blue ground have a deep greenish-gray color, tending to black. A few of them have a bluish tinge added to the gray, which in this case is darker than usual. The 40-centimeter and 20-centimeter dikes, which cut the "floating" Waterberg, have the lightest tints of all—yellowish gray with a greenish cast.

To the unaided eye the grain of the dikes shows remarkably little variation, the largest glinting grains of calcite in any dike being about 1 millimeter in diameter. A few of the narrower dikes tend to be a little finer-grained than the wider dikes. Measured under the microscope, the lustrous crystals of carbonate have the maximum diameters noted in Table II. The 15-centimeter dike and a few

others seem to show steadily a finer grain near the contacts than in the middle of the respective dikes, but at least half of the dikes do not exhibit the same characteristic.

In some of the dikes cutting blue ground, especially near the contacts, angular and also somewhat rounded xenoliths of compact,

TABLE II

Number of Specimen	Thickness of Dike (Cm.)	Maximum Diameter of Carbonate Crystals (Mm.)	Specific Gravity	Color
	Cutting Blue Ground			
3106.....	8	1.0	2.76	Medium-dark gray with olive-green tinge
3127.....	10	0.8	2.73	Medium-dark gray with olive-green tinge
3101.....	11	0.6	2.70	Very dark gray
3111.....	15	0.5	2.82	Dark gray with olive-green tinge
3109.....	24	0.5	2.82	Medium-dark gray with olive-green tinge
3116.....	25	0.3	2.80	Medium-dark gray with olive-green tinge
3118.....	28	0.5	2.78	Dark gray with olive-green tinge
3117.....	29	0.7	2.83	Medium-dark gray with olive-green tinge
3126.....	30	0.8	2.74	Dark gray with olive-green tinge
3112.....	58	0.5	2.81	Dark gray with olive-green tinge
3124.....	90	1.0	2.80	Dark gray with olive-green tinge, nearly
3069.....	120	1.0	2.82	Medium-dark gray with olive-green tinge
3107.....	125	1.0	2.84	Medium-dark gray with olive-green tinge, but a little darker
3122.....	600	0.7	2.79	Deep bluish gray, tending to black
	Cutting Waterberg "Floating Reef"			
3129.....	20	0.7	2.83	Rather light gray with a faint rosy tinge
3125.....	40	0.5	2.72	Rather light gray with pronounced olive-green tinge

completely serpentinized blue ground were found. Such inclusions are, however, too few to obscure the comparative uniformity of the material of each dike, from wall to wall and from end to end of each exposure (continuous through lengths of from 5 to 30 or more meters).

The 40-centimeter dike, cutting the large body of Waterberg beds, shows strong shearing at, and parallel to, each contact. Similar shearing was not observed in the case of the 20-centimeter dike which cuts the smaller mass of "floating" Waterberg, shown in

Figure 2. The contact between carbonate rock and quartzite is here clean-cut, and as sharp as the normal contact of an igneous dike.

Wagner described the blue ground surrounding the 60-foot mass of calciferous rock, quarried away since his visit, as "completely saturated with calcite and converted into 'harde-bank.'" The present writer could not find any special amount of carbonate disseminated through the blue ground near any of the dikes exposed in 1922. Analyses made within 20 centimeters from any contact would probably show no higher content of carbon dioxide than that given in the average of the kimberlite analyses of Table I, or in the analysis of the contact serpentine, Table V.

The minerals composing the dikes include calcite, magnetic iron oxide, serpentine, titanite, apatite, dolomite (?), periclase (?), and an amorphous substance generally blackened with a stain of granular iron oxide.

Relatively clear, anhedral individuals of calcite, either interlocked or in a kind of phenocrystic relation to a groundmass made up of the other constituents, constitutes most of the dike material. Very rough estimates of the percentage of calcite in each dike are given in Table IV. Dr. E. S. Larsen found the index of refraction to be that of calcite. This mineral is occasionally twinned, but, like the other constituents, bears no evidence of having been specially sheared since crystallization, except in the case of the 11-centimeter dike. Though the calcite has small inclusions of iron oxide and, less often, other constituents, it looks under the microscope like an early product of crystallization.

The serpentine forms a kind of mesostasis, as well as the xenoliths already described. Its habit is that of the compact serpentine of the exomorphic contact-shells. The titanite is anhedral; it often occurs in small granular aggregates, recalling leucoxene.

Since the powder of each dike rock is strongly magnetic, the many anhedral and cuboidal grains, which give the rock its dark color, are diagnosed as magnetite. Conceivably magnesioferrite is present.

Much of the groundmass inclosing the clear grains of calcite is composed of an amorphous, colorless to pale yellow substance, whose determination is not easy. One cause of obscurity is the rather

thorough staining of the substance with black, opaque granules, which appear to be chemically identical with the larger crystals described as magnetite. Using the refraction method, applied to the more transparent edges of the substance, Dr. Larsen concluded that the amorphous material may be a colloidal or metacolloidal form of magnesium hydrate—a view that checks well with the chemical analyses.

TABLE III

Constituent	1*	2†	3‡	4§
SiO_2	7.01	7.29	23.2	25.12
TiO_2	1.53	0.86	.....	.....
Al_2O_3	0.99	1.04	.....	.....
Fe_2O_3	8.06	2.23	.....	.....
FeO	3.84	1.58	.....	.....
MnO	0.68	0.35	.....	.....
MgO	24.82	3.74	21.2	.....
CaO	24.76	45.71	20.7	.....
Na_2O	0.39	not det.	.....	.....
K_2O	0.43	not det.	.....	.....
$H_2O-(105°)$	0.16	1.24	.....	0.30
H_2O+	9.61	0.54	.....	3.19
P_2O_5	1.22	0.67	.....	.....
S	.....	0.20	.....	.....
CO_2	16.93	34.88	14.82	25.12
Totals	100.43	100.33	.....	.....
Specific gravity	2.79	2.72	2.70	2.80

* Analysis of specimen 3122 600-centimeter dike, by E. G. Radley, Geological Survey of Great Britain, London.

† Analysis of specimen 3125, 40-centimeter dike, by Miss H. E. Vassar, Department of Mineralogy and Petrography, Harvard University.

‡ Partial analysis of specimen 3101, 11-centimeter dike, by H. E. Vassar.

§ Partial analysis of specimen 3116 25-centimeter dike, by H. E. Vassar.

In some of the thin sections a few small grains of a colorless mineral, with high single refraction and quite isotropic, are thought to be periclase.

Though all of the components listed above, except periclase, appear in every dike examined, the data of Table IV show considerable variety in the proportions of the different minerals. The proportion of calcite is nearly at minimum, the magnesium hydroxide at maximum, in the 600-centimeter dike (specimen 3122); and the calcite is nearly at maximum, the magnesium hydroxide probably at minimum, in the 40-centimeter dike (specimen 3125). According-

ly these specimens were selected for analysis. The results are given in Table III, where are entered also percentages of certain oxides in two other dikes, namely, the 11-centimeter (specimen 3101) and the 25-centimeter (specimen 3116).

On the assumption that the serpentine in the carbonate rocks has the composition of the contact serpentine, an analysis of which is given on a later page, these four analyses of the carbonate rocks have been calculated, with the result shown in Table IV.

TABLE IV

Constituent	1 (Specimen 3122)	2 (Specimen 3125)	3 (Specimen 3101)	4 (Specimen 3116)
$CaCO_3$	38.5	74.2	33.7±	57.1±
$MgCO_3$	.....	4.3	.....	.....
Serpentine	6.5	4.5	61.0±	39.0±
Magnetite	11.6	3.2		
$Mg(OH)_2$ (colloid)	28.6	.....	.....	.....
Apatite	2.7	1.7	.....	.....
Titanite	3.2	2.1	.....	.....
Ilmenite	0.5	.....	.....	.....
Periclase	2.4	.....	.....	.....
Orthoclase	2.2	.....	.....	.....
Albite	3.1	.....	.....	.....
Anorthite	.....	2.8	.....	.....
Water below 105°	0.2	1.2	.....	.....
$CaSiO_3$	.....	4.4	.....	.....
Sulphur	.....	0.2	.....	.....
Remainder	0.9	1.7	.....	.....
Totals	100.4	100.3	.....	.....

In specimen 3122, all of the CO_2 seems to be combined with the CaO; the indices of refraction of the carbonate in this rock are nearly or quite identical with those of calcite. The small amount of magnesium carbonate in specimen 3125 is occult. In specimen 3125 the assignment of silica and lime to calcium silicate is arbitrary. Otherwise the mode of 3125 is fairly well represented by the proportions given in the table. The proportions given for specimen 3101, the dike richest in serpentine, and for specimen 3116 are merely approximate, but are probably not far from the truth.

The amount of magnesium hydroxide in specimen 3122 is higher than in any other dike; this substance appears to be present in all of the dikes. The magnesia has two conceivable sources. If it origi-

nated in blue-ground material, incorporated by the carbonate-bearing solution, the corresponding amount of silica must have been removed and its place taken by hydroxyl. If, as periclase in solution, the magnesia accompanied the lime, which came from sediments at great depth, the magnesia must have been later hydrated, the water being derived from the buried sediments or from the blue ground or from both sources. The latter hypothesis, of derivation of the magnesia from sedimentary rock, is the simpler of the two, and is directly implied by what appears to be the best explanation of the much more abundant calcite, as outlined on a following page.

Rocks with the composition of specimen 3122 are rare. An analogy to it is found in a peculiar brucite-serpentine from Stevens County, Washington State, described by F. W. Clarke.[1] With the outward appearance of an ordinary serpentine, this rock contains 60 per cent of $Mg(OH)_2$, in the form of brucite, as shown by Clarke's chemical and mineralogical analyses:

Chemical	Percentage	Mineral	Percentage
SiO_2	13.08	Hydromagnesite	5
Al_2O_3	1.63	Chlorite	14
Fe_2O_3	1.25	Serpentine	20
FeO	0.19	Brucite	60
MgO	56.44	Extraneous matter	1
CaO	0.33		
H_2O, at 100°	0.85	Total	100
H_2O, above 100°	23.94		
CO_2	2.03		
Total	99.74		

Unfortunately, the geological relations and origin of the brucite-serpentine are unknown, so that one cannot tell how far this case is analogous with the highly magnesian dike of the Premier Mine. Equally remote is a decision as to the difference of conditions leading to the crystallization of the hydrate in the American rock and those forbidding its crystallization in the African rock.

The 40-centimeter dike cuts the Waterberg "floating reef." Specimen 3125, taken from that dike, contains a much smaller proportion of total iron oxides than specimen 3122, which cuts blue

[1] F. W. Clarke, *U.S. Geol. Survey Bull. 262* (1905), p. 69.

ground. The same contrast is found between the 20-centimeter dike, cutting the larger Waterberg body, and any one of the dikes cutting the blue ground. These facts suggest that the iron oxides have been largely derived from the blue ground itself, which was mixed with the carbonate material during the emplacement of the latter. The content of serpentine is, however, nearly the same in the two analyzed rocks.

Column 1 of Table V gives Miss Vassar's analysis of the compact serpentine (specimen 3112) which forms an exomorphic contact-shell, 2.5–4.0 centimeters thick, on each side of the 58-centimeter dike. Column 2 of the same table shows the mean of the three

TABLE V

Constituent	1	2	Constituent	1	2
SiO_2	37.56	38.15	K_2O	.09	.74
TiO_2	0.96	2.01	H_2O-	0.82	3.08
Al_2O_3	0.93	2.29	H_2O+	10.99	10.00
Fe_2O_3	7.89	6.82	CO_2	1.25	0.63
FeO	3.07	2.79	P_2O_5	0.40	1.33
MgO	33.89	28.19			
CaO	2.25	3.78	Totals	100.34	100.08
Na_2O	.24	.27	Spec. grav.	2.64	2.67

analyses of kimberlite stated in Table I. The compact selvage-like serpentine is very similar to the average kimberlite, and it seems about as clear that the shells are due to metamorphism by the dikes themselves.

ORIGIN OF THE DIKE MATERIAL

The existence of primary magmatic carbonate has long been recognized. In his memoir on the Fen region of Norway, Brögger has recently summarized existing knowledge on the subject. He startled petrologists with his announcement of two kinds of dikes in the district: sövites, with 67 to 80 per cent of calcite and 1 to 13 per cent of dolomite; and rauhaugite, with 89 per cent of a slightly ferruginous dolomite.[1] On the other hand, Bowen believes these carbonates to have been introduced in water solution, replacing

[1] W. C. Brögger, "Die Eruptivgesteine des Kristianiagebietes, IV," in *Videnskapsselskapets Skrifter*, I, mat. naturv. Kl., No. 9 (1920), pp. 231, 250.

silicates.[1] Because of the very high vapor tension of dolomite at magmatic temperatures, it is indeed doubtful that this mineral could be formed directly from a magma containing less than 10 per cent of water or similar flux. The same difficulty does not apply in the case of calcium carbonate, which has a considerably higher temperature of dissociation. Barbour has suggested that the dominant calcite of certain vein-like bodies in China is of direct magmatic origin.[2]

Undoubtedly many "veins" of marble represent injections of plastic, metamorphosed limestone in the solid state, but the plasticity may have been greatly increased through the development of interstitial liquid, this liquid being the result of mutual solution of undissociated calcite, the products of the dissociation of calcite, and connate water. Increase in the relative proportion of such a solution would give a transition from the state of solid-plasticity to the state of liquid-viscosity for the carbonate material.

Wagner's conclusion that the tabular masses of carbonate rock in the Premier Mine are true dikes and not veins seems so clear in the field as to be beyond controversy. Less satisfactory is his assumption of an original peridotitic (kimberlite-like) constitution for the dikes, with the accompanying explanation of their present calciferous character by "hydrothermal action as a sequel to the volcanic outbursts" (p. 77 of his book). He mentions two reasons for entertaining the hypothesis of hydrothermal replacement, though he also indicates the difficulty of putting full faith in the hypothesis.

The first reason is the presence of pseudomorphs of serpentine after olivine in the deeply weathered phase of the dike material. Yet all but one of the fourteen dikes studied microscopically by the present writer show nothing that can be readily construed as a pseudomorph of the kind. In the thin section of this exceptional dike a few millimeter-long grains, composed of serpentine and carbonate in variable proportion, have outlines somewhat like those of euhedral olivine. These may be true pseudomorphs, but it must be remembered that occasional altered olivines appear in the xenoliths of the dikes. The bodies in question may therefore be xeno-

[1] N. L. Bowen, *Amer. Jour. Science*, Vol. VIII (1924), p. 1.

[2] G. B. Barbour, *Bull. Geol. Soc. China*, Vol. II (1923), p. 49.

lithic. In any case they are too rare, even within the unique dike known to carry them, to give good warrant for the replacement hypothesis.

Wagner's second reason, already noted, is that the blue ground around the 60-foot mass of calciferous rock, exposed before the year 1914, was impregnated with calcite. This would be the expected kind of penumbra for every dike, if the replacement hypothesis were correct, since the wall rocks were doubtless as porous as the assumed original rock of the dikes. However, special concentration of carbonate was nowhere observed in the blue ground adjacent to the dikes which were exposed in 1922.

A further objection to the replacement hypothesis appears when one considers the striking degree of chemical, mineralogical, and textural uniformity of each dike, as well as the general similarity of the group of dikes among themselves. In this connection, a glance at the list of specific gravities, Table II, is instructive. The imagined replacement could hardly affect so uniformly the whole thickness of each dike, from wall to wall, and also all of the dikes, wide as well as narrow.

Nor would carbonates which were deposited hydrothermally have such small range of size of grain as that actually observed throughout the whole assemblage of dikes. Relative uniformity of grain for the crystals is consistent with the hypothesis of a primary, magmatic origin for the calcite. On the other hand, this hypothesis is not weakened by the discovery of a slight diminution of the grain-size toward the contacts of a few of the dikes.

The complete welding of the carbonate rock with the exomorphic contact-shells of serpentine is also difficult to understand on any other theory than the one here proposed. Both the welding and the metamorphism of the blue ground are at once explained if the dike material was originally gas-charged, carbonate magma. The interaction of that magma and the wall-rock, itself abundantly charged with water and perhaps hot, might well lead to metamorphism of the blue ground, which was as complete as that actually observed. In the presence of so much volatile matter, comparatively rapid mixing of the friable wall-rock with the carbonate magma, as this magma was forced thousands of meters up through the blue ground, might

be expected. How intimate the mixing may be is shown by the partial analysis of the 11-centimeter dike (see column 3, Table III, and column 3, Table IV).

Wagner emphasized the difficulty of accounting for the large amount of carbonate in the South African kimberlite pipes; one must agree with him that this general problem is still open. In the case of the Premier Mine pipe the mystery is not so dark, if one is prepared to admit the upward migration of carbonates derived from the Great Dolomite. From the present point of view, the main question relates to the possibility of the mutual solution of the components of the dolomite, with or without the aid of foreign material.

Because of the high temperature and pressure required, simple fusion of the dry, non-dissociated carbonates of the Great Dolomite cannot be postulated. On the other hand, partial dissociation and mutual solution of the resulting oxides and residual carbonates can take place at more moderate temperatures, especially in the presence of connate water. According to Boeke and Eitel, magnesium carbonate is considerably dissociated at temperatures well below that at which calcite is sensibly dissociated. If dolomite be heated to incandescence at a pressure of about 150 atmospheres, the $MgCO_3$ is dissociated to MgO and CO_2, while the $CaCO_3$ as such is dissolved with them, to recrystallize when the artificial magma is cooled.[1]

Covered, at great depth, by the thick Pretoria beds, massive sills of diabase, and the felsitic body, the temperature of the Great Dolomite must have been raised by general earth-heat before the kimberlite magma was erupted. Around the kimberlite pipe, just opened, the dolomite became further heated, with the development of vapor tension of both carbon dioxide and connate water. Is it unreasonable to suppose that some of the impure and gas-saturated limestone became truly magmatic and that this solution was forced into eruption by gas pressure?

Thus expressed, the magmatic hypothesis implies a genetic connection between kimberlite and carbonate rock, and a compara-

[1] H. E. Boeke and W. Eitel, *Grundlagen der physikalisch-chemischen Petrographie*, 2d ed. (Berlin, 1923), p. 520. For the dissociation temperatures and pressures of $MgCO_3$, see R. Marc and A. Simek, *Zeitschrift für anorganische Chemie*, Vol. LXXXII (1913), p. 45, and W. Manchot and L. Lorenz, *ibid.*, Vol. CXXXIV (1924), p. 315.

tively short interval of time between their eruptions. No field observation made is opposed to belief in both of these deductions.

Passing through the kimberlite breccia, the carbonate magma would be likely to inclose some of the moderately silicious and hydrous rock of the walls of each dike. Such a process can account for the presence of serpentine and iron and titanium oxides in the carbonate rock, as well as partially digested xenoliths of blue-ground material.

Secondary magma should not be homogeneous; still less homogeneous should be the resulting rock. Depending on local differences of pressure and of the permeability of the dike walls, the ease of escape of the carbon dioxide would be variable. Hence the proportions of calcite, magnesium carbonate, other non-hydrous minerals, and hydrates in the solid dike-rocks could not be constant, apart altogether from differential solution of components of the wall rocks. The actual chemical and mineralogical variation of the dikes is thus not surprising if these dikes crystallized from so peculiar a magma. Inasmuch as calcite is more stable at high temperature than is dolomite or magnesite, the great predominance of calcite among the carbonates of the solidified dikes is easily understood.

SMYTH'S EXPERIMENTS ON THE FUSION OF THE DIKE MATERIAL

It was obviously desirable to test the hypothesis by experiment. Accordingly the writer appealed to Dr. F. H. Smyth, of the Geophysical Laboratory at Washington, who kindly investigated the behavior of the carbonate rock at high pressure and at various high temperatures. It is expected that the results will be published by Dr. Smyth in a separate paper, but he has generously given permission for their summary statement on the present occasion. This is done by quoting essential passages from his letters.

Since specimen 3122 (600-centimeter dike) and specimen 3125 (40-centimeter dike) represent the extremes of composition characterizing the dikes, they were selected for the tests.

All the heatings were made with finely powdered material, inclosed in sealed platinum tubes and under an external pressure of

2,000 atmospheres. Each charge contained about 0.05 gram of the powder.

In the first series of experiments four charges, consisting of specimen 3122 alone, specimen 3122 with 10–14 per cent of water, specimen 3125 alone, and specimen 3125 with 10–14 per cent of water, were used. Heatings were made at 750°, 850°, and 1,030° C.

Microscopic examination of the charges after the heatings showed that the results did not vary materially at the two lower temperatures. At 750° the $Mg(OH)_2$ had lost its water and become definitely crystallized periclase. Samples of specimen 3122, sealed "dry," were distinctly moist with liquid water given off by the $Mg(OH)_2$, even at the lowest temperature at 2,000 atmospheres pressure. The periclase was slightly tinted with iron; however, there appeared to be no change in the residual magnetite, which remained exceedingly fine-grained. Only the most minute quantities of the magnetite, if any, could have been in solution under the conditions of any of the experiments.

Specimen 3125 lost a small amount of CO_2 at the lowest temperature. This was shown by the fact that there was a distinct residual gas-pressure in the tubes containing specimen 3125 when they were removed from the furnace. This CO_2 came from the $MgCO_3$ present, the heated charges containing crystallized periclase in small amounts. Such an effect is quite in accord with the behavior of $MgCO_3$, which loses CO_2 at low temperatures and at high pressures, and does not readily reabsorb CO_2 after crystallized periclase has once formed.

The calcite present in both dikes behaved quite as it would if it were present alone with some added water. At 750°, where $CaCO_3$ is distinctly more soluble in water than at ordinary temperatures, some recrystallization had already started after the lapse of twenty minutes. At 850° this recrystallization was still more advanced. At both these temperatures there was a slight segregation of calcite at the tops of the tubes, showing that the supernatant solution of $CaCO_3$ in water had allowed the main mass of material to remain in the bottom of the tube. On cooling, this solution redeposited pure $CaCO_3$ above the rest of the material. However, the main mass of $CaCO_3$ remained quite unchanged. Hence, in these cases there was

no "fusion" of $CaCO_3$ in water, nor was any large amount of $CaCO_3$ transported in aqueous solution, though such solutions are surely more concentrated than they are when cold.

At 1,030° the calcite was really fused. This was true of all samples, with or without water. The "dry" sample of specimen 3125 contained periclase, which is known to dissolve in molten calcite and greatly to lower its fusion temperature. Small quantities of glass from the silicates present also aided in the fusion. Except for the completely recrystallized calcite, the samples remained quite similar to those which had been heated at lower temperatures.

At 750° and higher temperatures the $Mg(OH)_2$ and $MgCO_3$ could not have failed to be decomposed, even if the pressure had been much higher than 2,000 atmospheres.

No evidence could be found that the magnetite was ever in solution with the rest of the dike material; on the other hand, the magnetite may have been in mechanical mixture with the latter.

A second series of experiments were made at a temperature of 950°. The charges consisted of: (1) "dry" specimen 3122, (2) 3122 with added water, (3) pure calcite plus 25 per cent of water by weight, (4) pure calcite plus 1 per cent of water by weight. The calcite charges with water were used as controls to see whether, if consolidation or "fusion" in the charges of dike material took place at 950°, the pure calcite also would fuse at this temperature in the presence of water.

In the case of the dike material, the result did not differ from that at 1,030°. The material appeared well consolidated, as if fusion had occurred; the product was composed of calcite, periclase in large grains, unchanged magnetite, and very small quantities of glass. Hence at 950° the dike material had become very largely liquid, with the exception of the magnetite, which was not affected.

The calcite "controls" showed no evidence of complete fusion at 950°, even in the presence of 25 per cent of water. A growth of the crystals occurred, but the mass as a whole remained granular and unconsolidated. The lowering of the fusion temperature of the dike material to some temperature between 850° and 950° must, then, be attributed to the presence of the periclase and small amounts of silicates in the dike material.

Dr. Smyth agrees that the magnetite was probably derived from the blue ground. He finds it "reasonably certain" that specimen 3122 (and probably 3125), when heated to 950°, contained much fused, and probably very fluid, material. The mobility of the mass at 950° or at a little lower temperature would thus permit of its eruption in dike form.

Yet Dr. Smyth points out that if the dikes were igneous injections, they could not have crystallized at high temperature, so as to give their actual mineralogical composition. Neither the magnesium hydroxide nor the magnesium carbonate could have retained their volatile components. Both would have been decomposed, with the production of periclase in each case. Under the conditions of nature the periclase would not be likely to be reconverted into either the hydroxide or the carbonate at high temperature. Dr. Smyth concludes: "To explain the presence of a large proportion of the dike material, namely the $MgCO_3$, $Mg(OH)_2$, and very likely the magnetite, we must resort to the assumption of the action of water after the formation of the dike." He asks: "Does this not establish a presumption that the calcite present may also have been much affected or may also be of secondary origin?"

In this connection it should be remembered that $MgCO_3$ can hardly be rated as more than an accessory constituent of any of the dikes, and that $Mg(OH)_2$ is really abundant only in the 600-centimeter dike (specimen 3122) and probably makes up no more than 5 to 10 per cent of the other dikes. Secondary (or late-magmatic, low-temperature) carbonation and hydration need be postulated, therefore, only for some 5 to 15 per cent of the average dike.

Dr. Smyth believes that his experiments "support the idea that hot waters under pressure may be an efficient agent in the transportation of calcite and its deposition under conditions which might make it appear 'primary,' " but adds: "to speak of a 'molten' magma in such cases may be misleading."

The hypothesis that the carbonate rock has been deposited from ordinary, dilute vein-solutions, hot or cold, does not agree well with the field facts already described by Wagner and by the present writer. The difficulty of explaining the rock as due to the replacement of original silicates by carbonate and minor constituents of the existing dikes has also been indicated. It remains to inquire whether

the high-temperature experiments may point to a more successful solution to the puzzle.

Dr. Smyth emphasizes the necessity of crediting the formation of the magnesium hydroxide and the much less abundant magnesium carbonate to the introduction of the volatile components during a period of relatively low temperature. In fact, the local, if not general, temperature of the strongly hydrous blue-ground was doubtless high enough to enforce the prolonged diffusion of water through the body of each dike during the later stages of its crystallization. The nearly complete hydration of the periclase, crystallized from a true magma, may have thus resulted. Similarly, the diffusion of carbon dioxide at the lower temperatures can account for the magnesium carbonate, which at maximum forms only a small percentage of the mass of any of the dikes. In other words, a moderate degree of alteration, controlled by volatile matter, seems to be readily postulated without invalidating the view that the dike material (excluding the foreign serpentine and magnetite) was originally magmatic and dominantly calcitic.

Dr. Smyth's experiments prove the temperature necessary for the magmatic stage to have been not much higher than 900°. It may have been decidedly lower, for the system has probably lost both carbon dioxide and water since the dike material was emplaced. In any case, the magmatic hypothesis does not demand an unreasonably high temperature. Another important condition for a comparatively low temperature is the mixture of the periclase molecule with the calcite. Just such a combination is expected, if the carbonate magma was generated by the dissociation of the magnesium carbonate of the Great Dolomite. The presence of the fluxing water is readily assumed when one considers the hydrous nature of all the sediments traversed by the kimberlite magma, those sediments having become considerably heated by deep burial and by injection of the kimberlite melt. Moreover, as above noted, the water of the deep-seated kimberlite itself could hardly fail to be important.

CONCLUSION

As Dr. Smyth points out, the hydration and carbonation of the magnesia in the dike material must have taken place at a temperature well below 700°, and in a sense were secondary, not directly

magmatic, processes. His query, whether it is not logical to assume a similar low-temperature origin for the dominant calcite of the dikes, this carbonate being introduced in dilute "vein" solution with water, is entirely reasonable, and is pretty certain to be raised by anyone who is not personally acquainted with the facts of the South African field. Indeed, Wagner himself decided for the secondary origin of the calcite as the most probable, though recognizing obvious difficulties with this interpretation. For reasons described in the foregoing pages, the present writer cannot accept either the replacement hypothesis or the "vein" hypothesis for the great bulk of the dike material.

The dikes are, then, regarded as essentially magmatic, though somewhat modified by the invasion of water-gas and carbon dioxide toward the close of the cooling process. Clearly, too, some of the dike material consists of xenolithic blue ground, which was never dissolved in the carbonate magma, but was strewn about in the magma as this was forcefully injected up, many thousands of feet, through the kimberlite. Conceivably some of the calcite was solid from the start, and represented undissolved, xenolithic material from the Great Dolomite. However, for this supposition there is no evidence. Nor is there any fact supporting the guess that the dike-like bodies were injected as solid, but specially plastic, masses.

Referring the source of the carbonate material to the deep-seated Great Dolomite is the second main speculation of this paper.

Neither of these hypotheses can now be proved. Their publication will help to advertise the existence of important problems regarding bodies of carbonate rock, the like of which has apparently never been seen outside of the Premier Mine. It should be noted also that the Premier pipe is one of the very few kimberlite pipes which traverse the Great Dolomite; the geological conditions seem to be almost as unique as the dikes themselves.

THE GEOLOGIC RÔLE OF DILATANCY

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ABSTRACT

Dilatancy, the expansion of granular masses when deformed due to the rearrangement of the grains, was described and illustrated with many interesting experiments by Osborn Reynolds, an English physicist. In this paper the term is used in a broader sense to include all volume increase due to deformation. The consequences of dilatancy by deformation have far-reaching geologic significance. It is suggested that dilatancy is important in inducing faulting and jointing in unconsolidated sediments, in the movement of fluids—oil, water, and gas—contained in rocks, in initiating magmas and in certain of the processes accompanying intrusion and crystallization of magmas. The factors controlling the manner of deformation of unconsolidated granular masses are applied by analogy to a consideration of the manner of deformation of solid rocks by fracture and by rock flowage.

Dilatancy. The property of granular masses of expanding in bulk with change of shape. It is due to the increase of space between the individually rigid particles as they change their relative positions.—*Century Dictionary.*

This property of granular aggregates was described by Osborn Reynolds,[1] whose interest was apparently confined to its application in his mechanistic conception of the ether as applied to the development of a theory of gravitation. Dilatancy is a property of many earth materials, and is fundamentally related to the manner of response of these materials to deformation. It is the purpose of this paper to indicate the possible rôle of dilatancy in certain geologic processes. The term will be used in a somewhat broader sense, to include all volume increases due to deformation.

DILATANCY IN DEFORMATION OF INCOHERENT GRANULAR MASSES

Hard, spherical grains, such as shot, shaken down in a container, tend to arrange in a condition of maximum-density packing. If the grains are spherical and of uniform size, each grain is in contact with twelve neighboring grains. This arrangement has a minimum of voids, 25.9 per cent. It is obviously impossible to change the shape without increasing the volume of this aggregate (assuming that the

[1] Osborn Reynolds, *Scientific Papers*, Vol. II (1901), p. 217.

grains are not deformed), as any differential movement between the grains involves a change in the system of packing, which of necessity requires increase of voids and consequently of volume. This is illustrated in Figure 1, by a cross-section of spherical grains in close packing at the left, and the increase in volume occasioned by deformation of this mass at the right.

A mass made up of spherical grains of uniform size serves best for illustrative purposes. The property of dilatancy, however, is not

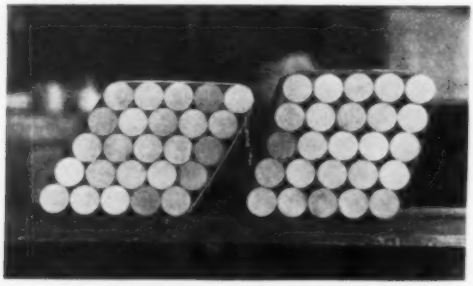


FIG. 1.—Illustrating the increase in voids and consequent increase in volume resulting from deformation of a mass of close-packed spherical grains. Cylinders of wood held by rubber bands and strips of cardboard serve to represent spherical grains in cross-section. This serves as a two-dimensional representation of dilatancy.

confined to masses of spherical grains, but is common to all granular aggregates, regardless of angularity of grains or degree of assortment.[1]

Quoting Reynolds, "The most striking evidence of dilatancy is obtained from the fact that since dilatant material cannot change its shape without increasing in volume, by preventing change of volume all change of shape is prevented."[2] This fact is beautifully illustrated by one of Reynolds' experiments. A toy rubber balloon, filled with sand and containing just sufficient water to saturate the

[1] When particles are so small that the adsorbed liquid or gaseous layers on their surfaces are thick in proportion to their radii, movement between the particles apparently takes place through deformation of the envelopes. This is illustrated by the behavior of aerated, fine dry powders, which simulate fluid in their behavior, and by damp, fine-grained clay.

[2] Osborn Reynolds, *Nature*, Vol. XXXIII, p. 30.

sand after it has been shaken down into a condition of dense packing, resists deformation to an astonishing degree, because sand so contained, when deformed, must increase in volume, and requires more water than is available to fill the increased proportion of voids. The result is that the fluid pressure within the container is greatly reduced and atmospheric pressure forces the rubber very tightly about the mass of sand, preventing dilation, increasing intergranular friction, and thereby inducing rigidity. The tensile strength of the water may also be a factor in the rigidity of the mass. When deformed (although Reynolds, not being interested in this phase of the experiment, makes no mention of it) it fails along definite shear planes, rather than by plastic yielding of the entire mass.

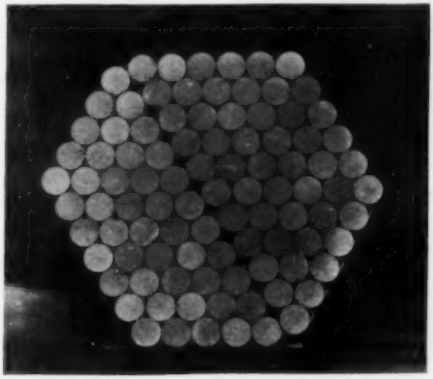


FIG. 2.—Wooden cylinders in triangular packing are held together by several very strong rubber bands. Increase in area is restricted by the containing pressure of the bands. One-sided pressure results in failure by shear with increase in area as shown. If increase in area is not prevented, the "grains" are all free to move relative to one another and single fractures as shown above do not develop.

The same phenomenon can be illustrated by a modification of Reynolds' experiment. If a rubber container, such as a toy balloon, is filled with sand and the air is pumped out, atmospheric pressure forces the rubber tightly against the contained sand, and the mass becomes exceedingly rigid. An 8-inch rubber balloon filled with dry sand and exhausted by an ordinary laboratory aspirator becomes as rigid as a solid rock, and gives out a musical tone, as does a stoneware jar, when struck with the knuckles. Rigidity is due to the containing pressures, but probably also to removal of air cushions from between the grains, both factors increasing intergranular friction. This evacuated, sand-filled, rubber sack behaves as a brittle solid,

which fails by shear when deformed under pressure. A thin-walled cylinder filled with sand (with a small proportion of flowers of sulphur to serve as a binder), closed at both ends, and evacuated, fails along a definite shear plane under longitudinal pressure. By heating the deformed cylinder to the melting-point of sulphur, the mass of sand is solidified. Such a mass is illustrated with the container removed in Figure 3. Granular masses free to dilate deform by flow; when dilation is prevented or restricted, deformation causes fracture. Sand, either wet or dry, under relatively slight containing pressures, behaves essentially as a solid (as dilation is restricted) and, when deformed, fails largely by fracture along shear planes. This manner of failure requires a minimum increase in volume and involves dilation only in the shear zone. Plastic deformation of close-packed grains involves the entire mass deformed, and causes a much greater volume increase than that required by failure along definite shear planes.

FIG. 3.—Failure by shear of dry sand held in a cylindrical rubber container and made rigid by pumping out the air. The mass was deformed by longitudinal compression.

The mechanical properties of fine, dry sand under no other containing pressures than its own weight are interesting in connection with the phenomena of dilatancy, and afford a means of simple experiments quite instructive in connection with problems of the mechanics of rock deformation. If sand, fine enough to pass through an 80-mesh screen, is poured out on two overlapping sheets of paper so that the pile of sand is partly on one sheet and

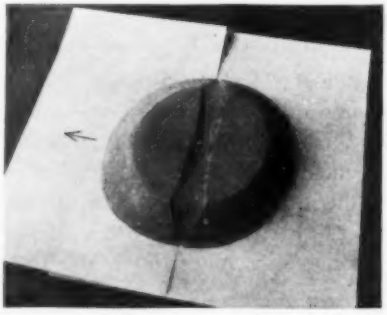


FIG. 4.—Graben fault in fine, dry sand, developed by moving the upper sheet of paper in the direction of the arrow.

partly on the other, and is leveled off to a thickness of approximately 2 cm., a graben fault may be produced by pulling the upper sheet of paper away from the lower in a direction at right angles to its covered edge. See Figure 4. If, with the sand again prepared as above described, the upper sheet of paper is moved *toward* its covered edge, a wedge of sand will be faulted upward in a horst. See Figure 5. If the upper sheet of paper is rotated about a point at its edge beneath the sand, a combination of graben and horst is produced. See Figure 6. If the sand is leveled out, as previously described, in a layer 2 cm. thick, and a small block is thrust slowly into the mass by sliding it along the paper, the sand displaced in front of the block will rise and override the undisturbed sand in a series of overthrust faults,[1] resembling in a rather striking way the well-known structure of the Scottish Highlands. In this case the easiest relief is upward, and movement is accomplished by faulting in this direction. If the sand is piled into a rather long, narrow ridge, as in Figure 8, and the block is thrust longitudinally into the ridge of sand, the direction of easiest relief is lateral, and the sand faults along nearly vertical planes at an angle to the direction of the movement.

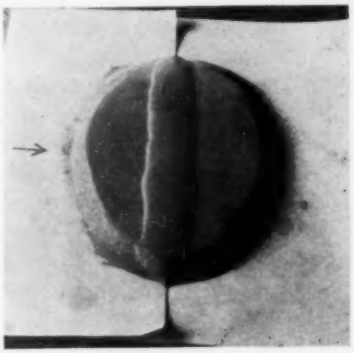


FIG. 5.—Faults producing a horst in fine, dry sand, developed by moving the upper sheet of paper in the direction of the arrow.

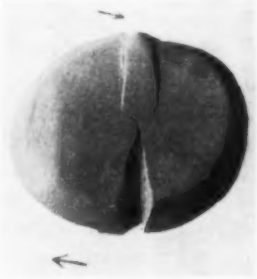
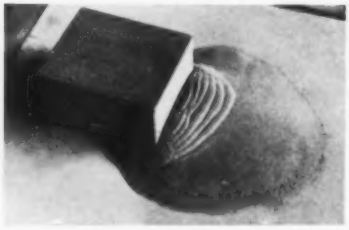


FIG. 6.—Combination of graben and horst produced by a rotational movement of one of the overlapping sheets of paper, as indicated by the arrows.

[1] R. T. Chamberlin and F. P. Shepard have described repeated overthrust faults in unconsolidated sand (*Journal of Geology*, Vol. XXXI [1923], pp. 511–12). Faults in

The geologic significance of the previously described properties of sand and allied granular aggregates is that even under very moderate load they tend to fail by fracture rather than by plastic flow, and that joints and faults in unconsolidated sediments are to be expected. The faulting and jointing in fine-grained glacial material so commonly observed (and so frequently marveled at) exemplify this property of granular aggregates. It seems probable that at least part of the jointing in sandstones and other sedimentary rocks may have had its origin in the deformation of these rocks prior to consolidation. The" grain" (a capacity to split along parallel surfaces across the stratification), so common in sandstones, may be the result of more open packing of the grains along planes of precementation dilatation.



a

FIG. 7*a*.—Repeated overthrust faults in fine, dry sand, developed by shoving the wooden box horizontally along the paper into the flat mass of sand. The direction of easiest relief is upward.

b

FIG. 7*b*.—Cross-section of faulted mass developed as shown in Figure 7*a*. Stratification is produced by sifting alternate layers of sand of different colors. The sand is cemented after deformation by heating the mass to a temperature sufficient to melt a small proportion of sulphur which had been incorporated in the mass.

EFFECT OF DILATANCY ON THE MOVEMENT OF FLUIDS CONTAINED IN SEDIMENTS

The changes in the manner of packing of grains, with consequent changes in voids, involves a movement of any fluids which may be contained in the voids.

unconsolidated sand and clay were produced by thrusting a pressure block horizontally into the mass. The nature of the faulting was tested by means of straws stuck into the sand and by the action of the moving sand on smoked glass plates inserted in the mass at right angles to the pressure block.

An experiment illustrating this may be made by filling a thin-walled rubber cylinder (a section of automobile tire tubing) with sand, tightly closing the ends with large corks, and filling the voids in the sand with water to the point of complete saturation. If a glass tube is inserted through a hole in one of the corks and bent at right angles to a vertical position and partly filled with colored water it serves as an indicator of the change in volume of the sand. It is found that this sand-filled cylinder cannot be bent or squeezed or deformed in any manner without lowering the level of the water in the vertical tube. This suggests that there must be a movement of contained fluids in sediments toward regions of deformation, as these are regions of dilatation, due to both rearrangement of grains and to rock fracture. It is believed that this phenomenon should not be neglected as one of the processes controlling the movement of oil, water, and gas, and as one of the reasons for the movement of oil toward anticlines and monoclines.

FIG. 8.—The sand was piled in a narrow ridge and the box thrust longitudinally into the mass. The direction of easiest relief is lateral and the sand faults along nearly vertical planes inclined to the direction of the movement.

It has been shown that if the amount of fluid in the granular aggregate is only sufficient to fill the voids in the condition of maximum-density packing, the mass fails largely by fracture, and not by plastic deformation. If fluid is available slightly in excess of this amount, the aggregate is easily deformed plastically up to the point where the increased voids absorb the available fluid. At this point the mass becomes rigid. This is well illustrated by a toy balloon filled with sand and water, with the latter somewhat in excess of the amount required to saturate the sand in a condition of dense packing. The balloon so filled is soft and easily deformed *up to a certain point*. If squeezed in the hand, it suddenly becomes rigid when the volume of voids and the volume of water become equal. If more water is added, a condition is reached where the balloon is soft

and easily deformed to any extent without becoming rigid. There is enough water present to fill the voids when the sand is in the most open arrangement possible. In this condition deformation does not involve an increase in volume of the balloon, and the mass changes its shape by plastic flow and offers very little resistance to deformation. This state of affairs is illustrated in nature by quicksand, which contains sufficient water to permit the most open arrangement of the grains—usually found in a situation where an upward current of water keeps the sand in open packing. Quicksand becomes very firm when this excess of water is drained away.

The mechanics of certain types of landslides, of mud flows, of failure of earth dams, involve in a large measure the factors of dilatancy. A comparatively small change in the water content of a mass of earth or sand changes it from a stable, comparatively rigid condition to a relatively fluid condition. Initial movement of the mass is an important factor, as it causes dilatation, which increases the voids, draws in water, and causes the mass, on passing the critical point, to move as a fluid.

DILATANCY IN THE DEFORMATION OF SOLID ROCKS

It is convenient to refer to the hard grains as the solid phase and to the material between the grains as the fluid phase. Using these terms, then, the experimental work seems to demonstrate two general principles. (1) When the fluid phase is sufficient only to fill the voids with the grains in a condition of maximum-density packing, deformation of the mass requires increase in volume. (2) When the available fluid phase is sufficient to fill the voids with the grains arranged in minimum-density packing, the mass may be deformed to any extent without increase in volume.

The writer believes that this conception can safely and profitably be carried over to a consideration of the mechanics of deformation of the solid rocks. Rocks in general may be regarded as granular aggregates. To the extent that they are porous, the pores represent the volume of a fluid phase, but the amount of fluid phase is, with the exception of a few special cases, too small to play much part in determining the manner of deformation. A sandstone, if cemented sufficiently to merit the term, has less porosity than sand. The small proportion of a fluid phase causes all solid rocks at or near the surface

to yield to deformation by fracture, with increase in volume. This fracturing of rocks clearly involves dilatation, and the net volume of the fractured mass has been increased by the total volume of the openings produced.

That the deformation of brittle materials involves an increase in volume *prior* to their failure has been generally recognized. Bucher[1] has discussed this matter in a consideration of the mechanical interpretation of joints, and quotes Chwolson, who gives a formula connecting the modulus of volume increase with Young's modulus and Poisson's ratio. He also quotes the work of Kahlbaum and Seidler, and of Lea and Thomas, as giving experimental evidence for increase in volume accompanying deformation under one-sided compression. That this increase in volume occasioned by deformative stresses imparts a greatly increased rigidity to the rock when under great containing pressures appears very probable. Bucher offers no explanation of how this increase in volume is accomplished, whether by change in the physical nature of the material itself, or by the development of voids.

When rocks are deformed under certain conditions involving high confining pressures and a proper rate of application of deforming stresses, they yield to deformation by plastic flow with the development of schistose textures characteristic of rock flowage. This manner of yielding to deformation does not involve a general fracturing of the rock, and probably does not require increase in volume. If the analogy of the requirements for plastic deformation of an unconsolidated granular mass be carried over to the case of rock flowage of a solid rock, it is necessary to conceive of the latter as consisting of a solid phase of hard grains and of a fluid phase surrounding these grains of a sufficient amount to permit the movement of the hard grains without occasioning dilatation of the mass by their interference. The solid phase is represented by the harder, more resistant minerals. The fluid phase is represented by those constituents of the rock which are relatively mobile, as evidenced by their rearrangement to schistose structures through processes of crystallization and recrystallization. This involves a complete atomic or molecular rearrangement of that portion of the rock.

[1] Walter H. Bucher, *Journal of Geology*, Vol. XXIX, p. 1.

Solid rocks in general, then, may be considered as granular aggregates consisting of a solid phase and a *potentially* fluid phase, which is caused to function as a fluid phase under certain conditions of composition, pressure, temperature, and rate of deformation. To make this clear let us revert for the time being to a modification of the simple concept of a granular mass consisting of sand and water. In this case a mass of sand, well shaken down into close packing with the voids filled with asphaltum instead of water, is used. The sand grains constitute a solid phase, the asphaltum a potentially fluid phase. A block of this asphalt-cemented, closely packed sand cannot fail except by fracture, even if deformation is applied very slowly, because the amount of fluid phase is not sufficient to permit plastic deformation. If, however, a mixture of sand and asphaltum be taken, with sufficient asphaltum to permit freedom among the sand grains equivalent to that in cubic or minimum-density packing, the resulting aggregate is such that under slow deformation at ordinary temperatures, or under more rapid deformation at higher temperatures (under which the asphaltum would soften), it would yield by plastic deformation of the entire mass without increase in volume. The asphaltum, or potentially fluid phase, would function as a fluid. If, on the other hand, the aggregate is deformed rapidly, the asphalt would not be able to function as a fluid, and the mass would fail by fracture, with an increase in volume.

This analogy of the asphaltum-sand aggregate may be applied to the flowage or fracture of rocks. Under conditions of rock flowage that portion of the rock which undergoes molecular or atomic rearrangement constitutes the fluid phase. If the rate of deformation under the existing conditions of temperature and pressure is too great to permit this rearrangement, the rock fails by fracture; and if the rate of deformation is slow enough to permit this rearrangement, failure is by plastic flow, provided the solid phase is sufficiently dispersed to prevent dilatation. If the amount of the fluid phase is intermediate, the deformation will be by combination of plastic flow and fracture, the grains of the solid phase being fractured and granulated through their mutual interference, the factures being filled by movement of the fluid phase into the openings; the net volume change is determined by the degree to which the increase of

volume due to fracturing of the solid grains is balanced by the decrease in volume due to development of new compounds of higher density in the fluid phase.

The zones of schist so commonly found marking planes of movement in massive igneous rocks differ in composition from the massive rock by having more combined water and less lime and soda. Mineralogically they are characterized by an increased amount of platey minerals, micas, and chlorite. That these schists may have been developed along zones previously weathered or hydrothermally altered is a possible explanation for the change in chemical composition. It is equally probable that the increase in water and loss of other constituents has in some instances been contemporaneous with the deformation of the rock along this zone. Because the development of a schist from a strong massive rock presupposes deep burial with intense rock pressures and deformative stresses of great magnitude, it has been difficult to reconcile the introduction of water, and the escape of constituents known to be lost, with the condition of great pressure, which on first thought would appear to tend toward the squeezing out of any water present and the prevention of any ingress of fluids. If it be assumed that deformation has been too rapid to permit the potentially fluid phase of the rock to function, there has been increase in volume as a result of deformation within the elastic limit, and as a result of crushing and fracturing. This dilated zone is a region of low *fluid* pressures, and any available fluids will move to fill these openings. Under the conditions of temperature and pressure they will have highly reactive and solvent properties, and metamorphic changes with the development of hydrous minerals would ensue. Continued and perhaps slower movement along this zone of yielding finds a rock partly adapted by composition to rock flowage, and any excess water, with a high content of dissolved mineral matter, is squeezed out.

It is interesting to speculate on the possible relationship of dilatancy to the manner of deformation of rocks at depth. The fact that yielding by fracture involves increase in volume, while rock flowage does not, suggests that the increased prominence of flowage with increase in depth is due to the fact that flowage does not require the lifting of the equivalent of the gravitational load, and therefore may

not require stress differentials as great as would be demanded for rock fracture.

DILATANCY AND ORIGIN OF MAGMAS

If the conclusion be accepted that deformation of a rock by flowage requires that the rate of deformation be slow enough to permit the potentially fluid phase of the rock to function as a fluid, and that deformation at a more rapid rate must of necessity produce failure by fracture, it follows that great and comparatively rapid deformations of the earth's crust may extend far below the surface and well into the zone normally characterized by rock flowage. If this is at a depth where the rocks are at a temperature above their melting-point but are kept solid by pressure, the result of fracture-dilatation would be immediate liquifaction of the rock in that zone to an extent measured by the increase in volume. This fluid rock migrating by way of the fracture zone to regions of lower pressure would remain fluid and contain sufficient excess heat to fuse a certain amount of rock in its path. The presence and movement of this fluid material would considerably upset the dynamic stability of the whole, and result in the development of magma and magmatic activities of greater or lesser extent, depending on the magnitude of the original deformation.

DILATANCY IN MAGMATIC PROCESSES

An igneous magma in the process of solidification can be considered as a granular mass made up of a solid phase (the mineral crystals) and a fluid phase. The mass has the properties of a fluid until solidification has proceeded to a point where the solid phase is so abundant that the grains are no longer free to move, but interfere with one another when the mass is deformed. In this condition the mass can no longer behave as a fluid, and is incapable of being injected into openings in the surrounding rock due to the great rigidity imparted to it by deformative stresses. It follows from this that plastic flow of igneous rock must occur before cooling has developed the solid phase sufficiently to make the mass potentially dilatant. After this potentially dilatant condition of the magma has been reached, it seems reasonable to suppose that any openings or fissures in the surrounding rock will be filled, not by movement of the magma

as a whole, but by the flowing out of its fluid phase under the fluid pressure of the liquid magma from the interior of the mass. This fluid phase would differ in composition from the solid phase, and consequently from the magma as a whole, by being in general more acid and containing a larger amount of mineralizers, in short, pegmatitic or aplitic in nature.

The potentially dilatant mass itself would also be capable of fracture under rapid deformation, and these fractures would be filled likewise by the fluid phase, resulting in thin dike-like occurrences of pegmatitic or aplitic material having vaguely defined, blending boundaries of the type so commonly observed in igneous masses.

Zones of deformation not resulting in fracture of the partly solidified magma would conceivably produce zones of more open packing of the solid grains, resulting in a greater proportion of the fluid phase and a consequent difference in composition of these zones of movement. If these zones of deformation or shear were closely spaced and parallel, as is quite reasonable, it is conceivable that the result would be a banding of the rock in the manner of certain of the primary gneisses.

Protoclastic structure may be developed by the interference of the solid particles during deformation of a potentially dilatant magma.

The movement of the fluid phase from the hotter portions of the magma would result in a reheating of the zone into which the hotter fluid magma migrated, with consequent interruption in the normal growth of a solid phase, cause re-solution, and the development of zonal growths of changed composition.

SUMMARY

Incoherent, granular masses, such as sand, in a condition approaching maximum-density packing, are dilated by deformation. In a condition of open packing they deform without dilatation. Prevention of free dilatation by enclosing pressures induces failure by fracture or shear when the mass is deformed, and with the development of joints and faults along thin zones of dilatation.

Deformation of a potentially dilatant mass causes *decrease* in

pressure of the fluid portion, and therefore fluids in rocks—water, oil, gas—move toward regions of dilatation.

The mechanics of response to deformation of incoherent granular masses is applied by analogy to solid rocks by conceiving of them as having a solid and a *potentially* fluid phase. When the latter functions as a fluid, the rock yields to deformation by flowing, otherwise by fracture.

Dilatation occasioned by deeply penetrating zones of fracture initiates magmas. Cooling magmas become potentially dilatant when the solid phase develops beyond a certain proportion. The fluid phase alone is then mobile and forms dikes and veins in the surrounding rock and in the granular mass itself. The flow of the fluid phase into cooler parts causes reheating of those parts.

THE JORDAN SANDSTONE[1]

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ABSTRACT

The Jordan sandstone is herewith redescribed and defined on the basis of the original description and a study of the type section together with numerous other outcrops in Minnesota and the adjacent states of Iowa and Wisconsin. Some of the important sections in Minnesota are given to show the sequence of beds and the general character of the formation over a wide area. Tentative identifications of part of the fauna are listed, and the conclusion is reached that the Norwalk sandstone belongs within the typical Jordan.

INTRODUCTION

The Jordan sandstone is the uppermost Cambrian formation of Minnesota and extends with a similar relationship over large portions of the adjacent states. In the artesian areas it is one of the important water-bearing formations, it being saturated with a good quality of water under pressure which it yields in generous quantities. Its characteristic loose, white to yellowish sand lying below the massive drab to gray or brown Oneota dolomite also forms a very dependable horizon-marker in drilling for the lower water-bearing strata, and the well drillers usually check their logs by this sandstone. It is therefore deemed worth while to present more fully the characteristics and importance of this great sand bed and to restate its limitations and place in the stratigraphic column of the Upper Mississippi Valley.

CLASSIFICATION

As developed along the Mississippi River and its tributaries, the St. Croixan series shows the following divisions and relationship to older and younger series:

Canadian or Ozarkian	Shakopee dolomite (New Richmond sandstone) Oneota dolomite

[1] Published by permission of the director of the Minnesota Geological Survey.

St. Croixan	Jordan sandstone St. Lawrence formation Franconia sandstone Dresbach sandstone Eau Claire? shale
Red Clastic	Hinkley sandstone Unnamed shales and sandstones

The St. Croixan is abundantly fossiliferous at numerous horizons, and there can be no doubt of its Upper Cambrian age. There may be some difference of opinion as to what formations should be recognized as independent divisions of it, especially in the lower part of the series, but that is of little or no importance in bringing out the points to be emphasized in this discussion.

NAME

In general it may be said that the division here discussed is that portion of D. D. Owen's formation 1 which he has designated the "Sixth Trilobite bed,"[1] but it is somewhat more inclusive in that it covers the sandstone immediately below that bed. The name, Jordan sandstone, was first used by Alexander Winchell in reporting on a study of the Belle Plaine brines which had been ordered by Governor Horace Austin in 1871.[2] It remained, however, for N. H. Winchell to describe the formation more fully and give it official recognition in the geological column of Minnesota[3] and the upper Mississippi region.

TYPE LOCALITY

The type locality Jordan, Scott County, Minnesota, was well chosen at the time these accounts were written. Active quarries were then in operation on the edge of the village; Sand Creek, flowing through town, plunged over a 10-foot cliff of the formation; the vaults at the breweries were excavated in a still lower horizon; the dug portions of the brewery wells showed the basal beds and contact with the St. Lawrence formation below, while the more massive

[1] Owen, *Geological Survey of Wisconsin, Iowa and Minnesota* (1852), pp. 52, 53.

[2] "Report of a Geological Survey of the Vicinity of Belle Plaine, Scott County, Minnesota" (16-page pamphlet), *Senate Document* (St. Paul, 1872), p. 10.

[3] "Geological Survey of Minnesota," *Second Annual Report* (1874), pp. 174–52.

upper beds are well shown a few miles down the river to the north along Van Oser's Creek, in the surrounding fields and in the adjacent river bottoms. Alexander Winchell's original section at Jordan[1] shows 51 feet of sandstone. N. H. Winchell's description, written a few years later, however, says that part of this may be a duplication of beds and suggests that the whole exposure may show as little as 25 feet of rock.[2]

A recent excavation at the upper highway bridge over Sand Creek exposed about 10 feet of sandy shales and thin-bedded sandstones immediately under the drift. These may be in part equivalent to the upper layers mentioned by Alexander Winchell, but they help to establish a total section at Jordan fully equal to the original measurement. At the present time, the old quarries, badly overgrown and partly filled with water, are abandoned, while the breweries have passed into history and their abandoned vaults no longer form an attractive addition to the section nor are the wells of easy access. The geologist who visits the region is therefore likely to be much disappointed with the exemplification of the formation and to fail to appreciate the magnitude of the sandstone of which he gets only an unsatisfactory glimpse at the type locality. Along the Minnesota Valley south of Jordan there are numerous outcrops of the formation. These expose a thickness of sandstone ranging up to 75 feet without revealing the underlying contact. Many of these outcrops are mentioned and partly described by N. H. Winchell in his earlier reports.[3]

ERRORS IN IDENTIFICATION

It is extremely unfortunate that the Jordan was confused with the New Richmond sandstone in the earlier discussions of the southeastern counties of the state.[4] Such an error as this, however, is not surprising in a new territory, and it doubtless crept into the work of the field men because the thin, northwestern edge of an upper sandstone member was overlooked along the Minnesota River where

[1] *Op. cit.*, p. 9. [2] *Ibid.*, p. 149.

[3] *Ibid.*, pp. 147–52; also *Eighth Annual Report* (1880), pp. 105–6.

[4] Winchell, "Geological Survey of Minnesota," *Fourth Annual Report* (1876), pp. 269–70; also *Final Report*, Vol. I, pp. 221, 252, 253, 284, 335, etc., and the accompanying county maps.

the Jordan and its associated formations were first recognized and defined, and the whole series of dolomitic beds above the Jordan passed under the name of Shakopee dolomite. When the work was carried to the southeast a prominent sandstone (New Richmond) was found between the two dolomitic limestones, and it was quite naturally assumed to be the Jordan, while at the same time the lower of these dolomites was confused with the St. Lawrence formation of the Minnesota Valley. Later well records in the vicinity of Shakopee revealed a much greater thickness of the dolomitic limestone than had been supposed to exist, together with a thin sandstone separating it into two more or less distinct divisions above the Jordan. The section in the two parts of the state then became clear, and N. H. Winchell was thus able to correct[1] the error himself. It need not therefore receive further consideration now except as a matter of caution to those looking up the original description of the Jordan sandstone or using the reports on the geology of the southeastern counties of Minnesota.

DELIMITATIONS

The original description of this formation might have been more extensive although it is adequate for its identification and much more complete than that of many others which are in constant use. In the sections and discussions as they have been corrected, N. H. Winchell positively states that the Jordan sandstone is the formation "lying next above the St. Lawrence limestone,"[2] and that it "immediately underlies"[3] the Lower Magnesian limestone. The lower portion of this latter has since been named the Oneota dolomite.[4] It is perfectly certain, therefore, that the formation named by Alexander Winchell and defined by N. H. Winchell the Jordan sandstone is limited below by the St. Lawrence formation and above by the Oneota dolomite or limestone. These are the limitations of the formation as accepted by numerous geologists throughout America, by

[1] *Fourteenth Annual Report* (1886), pp. 334–37; also *Final Report*, Vol. II (1888), pp. xiv–xxii.

[2] *Fourth Annual Report* (1876), p. 269.

[3] *Second Annual Report* (1874), p. 147.

[4] W J McGee, "U.S. Geological Survey," *Eleventh Annual Report*, Part I (1891), p. 331.

the United States Geological Survey, by the Geological Survey of Minnesota, and likewise by adjacent states. It is also clear that the type section at Jordan is in the lower part of the formation since the basal contact is there shown while the more massive, coarse, upper beds have been removed by erosion and are to be found in place in the Minnesota Valley only by traveling about 4 miles down from the town, or a greater distance up the valley.

The thickness of the formation ranges from 75 feet or more in the Minnesota Valley to 150 feet along the Mississippi River. Measurements of even 200 feet are sometimes assigned, but such great thickness is probably seldom attained and certainly unusual. It is composed of well-rounded quartz grains running from fine and medium to moderately coarse and occasionally containing a few small quartz pebbles in the upper, more massive beds. At some places in these upper beds, as along Van Oser's Creek 4 miles north of Jordan, the grains are reconstructed quartz crystals which maintain about the size of the coarser sand grain but show the crystal faces on all sides. This reconstruction must have taken place under unusual conditions, probably when the sand grains were bound together by a calcareous cement, as they are now very loosely cemented and have not grown together. Normally the sand is white to yellowish but may be brown or reddish-brown where the iron content is increased or where stained by circulating waters. Lamination and color banding are developed in some of the finer-grained beds at Jordan.[1] There is often very little cementing material, and the loose, white sand is shoveled from cliff-like sand banks and hauled away for building purposes. Exposed masses may be case hardened and resemble a quartzite, but on breaking through a thin shell the rock shows the same crumbling nature just described. In still other regions the rock is quite firm and might serve as a building stone. Cross-bedding is common in both the coarser and the finer beds, and some layers show ripple marks. Occasionally there are thin seams of a tough, greenish shale which in some places may have been "rolled" into balls 4 or 5 inches in diameter.

The lower part of the formation is much thinner bedded than

[1] See N. H. Winchell, "Geological Survey of Minnesota," *Final Report*, Vol. I (1884), p. 180.

the upper, and it is often difficult to determine the exact line of contact with the underlying St. Lawrence formation although the latter is more argillaceous and usually calcareous or dolomitic. At other places, such as near the Soo Drawbridge over the St. Croix River in northern Washington County, there is a well-developed basal conglomerate. Conglomerates, however, may appear at various horizons within the formation, and at this very place at least four others occur at higher horizons. Similar occurrences are not uncommon in some of the other Cambrian formations of this region. These are regarded as intraformational conglomerates similar to those commonly occurring in two or three of the overlying Ordovician formations. In most cases the pebbles consist of flat pieces of sandstone which resemble closely the materials of the matrix, and they are not unlike the flat-pebble conglomerates in the Upper Cambrian in Wyoming.

STRATIGRAPHIC RELATIONS

At some places the Jordan is overlaid unconformably (disconformably) by the Oneota dolomite, as at Stillwater or Afton; but more often this contact is likewise difficult to locate definitely although the uncertainty seldom affects more than a few feet. This seeming transition is partly due to the sandy condition of the basal Oneota and partly to the downward penetration of the calcareous waters from this latter formation which have cemented portions of the Upper Jordan into a very hard calcareous sandstone. In fact, so much of this calcareous material may be deposited in crystalline form within the upper beds that a freshly broken piece of the sandstone will glisten with the calcite cleavage faces. These harder layers usually alternate with others less favored in the cementing process and give rise to the peculiar, jagged-faced cliffs so common in the Mississippi bluffs. Where the upper part of the formation is shown along the Minnesota River, the Jordan-Oneota contact is usually sharp and the break in sedimentation is striking. At other places, however, there is some indication of a re-working of these upper beds by the advancing Ordovician sea. The evidence of this is not entirely satisfactory, but there is some change in the bedding and the introduction of argillaceous matter together with an unusual amount of iron. It must be admitted, however, that where this ir-

regularity is suggested it is extremely difficult to determine just how much of the sand may have suffered this disturbance, as there is no clear line of separation between the unmolested sands and those that may, on their fauna, be properly classed as younger. In fact, even above these beds the usual Oneota dolomite rests disconformably.

In order to have a clear idea of the Jordan sandstone at its type locality, it seems worth while to repeat here the original section at Jordan, Minnesota, as measured by Alexander Winchell.[1]

TABLE I

SECTION AT JORDAN, SCOTT COUNTY

	Feet
F. Sandrock, buffish, quite ferruginous, thick-bedded, seen at the mill...	6
E. Sandrock, ferruginous, thin- and irregularly bedded, friable and disintegrating, with many ferruginous seams, crusts, and concretions. In the quarry.....	3
D. Sandrock, irregularly whitish or ferruginous, heavy-bedded, obliquely and beautifully banded with iron streaks and laminae. In quarry.....	12
C. Sandrock, buffish, similar to D but thinner-bedded. In the quarry....	8
B. Sandrock, hard and ferruginous above, soft, friable, and buffish-red below. Falls of Sand Creek.....	10
A. Sandrock, whitish, compact. In the beer vaults, seen.....	12

This section was copied by N. H. Winchell in his original description of the Jordan sandstone,[2] and by Warren Upham in his account of the geology of Scott County.[3] In fact, the formation is founded on this section together with the outcrops along Van Oser's Creek near its junction with the Minnesota River. The upper part of the sandstone at this latter place is generally coarse and massive, but at Jordan these beds have been removed by erosion and the drift rests on the remnant of the formation either as given above or with slight addition. A few feet more at the bottom may be necessary to include the 10 feet of sandstone encountered in the "upper brewery" well,[4] and to complete the section down to the contact with the St.

[1] "Report of a Geological Survey of the Vicinity of Belle Plaine, Scott County, Minnesota" (16-page pamphlet), *Senate Document* (St. Paul, 1872), p. 9.

[2] "Geological and Natural History Survey of Minnesota," *Second Annual Report* (1873), p. 149.

[3] *Final Report*, Vol. II (1888), pp. 121–22.

[4] Warren Upham, *Eighth Annual Report* (1880), p. 104.

Lawrence, which was exposed when the well was dug, but this section shows the type of rock covered by the name Jordan and it is obviously the lower part of the formation. In fact, the St. Lawrence outcrops in the bottom of Sand Creek in front of the lower brewery, demonstrating, beyond a doubt, the relation of the Jordan to the St. Lawrence.

At the west end of the bridge over the Minnesota River at St. Peter, there is an excellent outcrop of the sandstone beds, which seem to have suffered redeposition, and that is probably the best locality for collecting the fauna characteristic of them. However, the contact with the Oneota is covered at that point and the following section, which shows this feature nearly as well, was measured at Kasota (see Fig. 1 for locations). This is the outcrop described by B. F. Shumard as "two miles above Traverse des Sioux," and the one from which he collected *Raphistoma minnesotensis* together with the "pygidium of a small trilobite," but the sandstone "was of such a friable character"[1] that he was unable to preserve the specimens. Kasota is located 35 miles south-southwest of Jordan. See Table II.

FIG. 1.—Sketch map showing locations of the sections given in the text.

Bed 6 of the foregoing section has always been included in the Jordan. The fauna, however, is too suggestive of the Ordovician to be ignored, and the layers carrying it are here referred to the basal part of the Oneota, but the materials in them must have been derived from the Jordan as it was worked over by the advancing Ordovician sea. The evidence of disconformity is not very clear. In

[1] *Op. cit.*, p. 484.

fact, the most striking break in sedimentation falls at the base of bed 8. This, however, is partly due to the marked change in the type of sediment laid down at that level. Moreover, it is thought possible

TABLE II

SECTION OF THE MINNESOTA RIVER BLUFF AND THE ADJACENT QUARRIES AT KASOTA, MINNESOTA

	Feet and Inches
Recent:	
15. Mantle rock—soil, clay, and limestone fragments	6 6
Oneota dolomite:	
14. Limestone, dolomitic, thin-bedded, partly weathered, brown	3 0
13. Limestone, dolomitic, hard brown layers	5 0
12. Limestone, dolomitic, pink to buff, of dense texture. These layers are the finest quarry rock	7 2
11. Limestone, dolomitic, gray to buff, hard, dense, unevenly bedded with numerous cavities	7 0
10. Shale, purple with some massive beds. This contains the Castile ledge	3 0
9. Covered interval probably including the "hummocky" layer of dolomitic limestone which forms the floor of the quarries	2 5
8. Limestone, dolomitic, gray to buff, mottled, thin-bedded, shown on river bluff. The base of these beds is very uneven	3 0
7. Clay or clay shale, gray to greenish	0 6
6. Sandstone, white, medium- to coarse-grained with numerous specimens of *Raphistoma minnesotensis* together with several other species of the same genus, several species of *Ophileta* and a trilobite. Bedding somewhat irregular	6 6
Jordan sandstone:	
5. Sandstone, white, medium to coarse, with streaks of green shale	6 0
4. Sandstone, white with pink to yellowish blotches, very soft, medium- to fine-grained, showing cross-bedding	12 0
3. Shale, argillaceous, green, which often gives place to a row of flattened, green, clay balls	0 3
2. Sandstone, white, medium-grained, almost without cement	8 0
1. Covered interval to level of Minnesota River	10 0

that the upper part of a loose, sand formation, such as the Jordan often is, might have been redeposited in the manner here suggested without leaving any trace of the line of division between the disturbed and undisturbed portions, although the former thus becomes part of a formation of widely different age. A somewhat similar condition occurs at St. Peter except that there is a little more evi-

dence of disturbance in the sandstone layers carrying the Oneota fauna. At the next place to the north, White Rock Bluff (Ottawa), where this horizon is well exposed, the Oneota dolomite rests disconformably on the Jordan and no trace of the *Raphistoma* fauna in either the sandstone or the limestone was found; also there appears to be no indication of redeposition of the sand at this place. A statement similar to this latter would be true for this contact at Mankato and the river bluffs adjacent thereto, but at Rapidan,[1] about 10 miles farther to the southwest, the same fauna again occurs in sandstones usually included in the Jordan.

A very excellent section of much of the Cambrian, showing especially the Jordan, is to be found at Dresbach on the Mississippi River about 25 miles north of the Iowa state line, and 140 miles east-southeast of Kasota. The section shown in Table III was measured at that place.

It is possible that the lowest beds exposed at Dresbach should be referred to E. O. Ulrich's Eau Claire shale, but the fauna is so similar to that of the typical Dresbach that they have not been separated from that formation. This section extends through the old quarries from which the Dresbach formation was named and is therefore the type, but it also gives an excellent idea of the Jordan sandstone in its typical occurrence along the Mississippi River. Mineral Bluff, a bare cliff standing out boldly at the north end of the village, shows the best outcrop of the Jordan. Here, as usual, it is a white to yellowish sandstone ranging from fine to medium or coarse grain, varying from thin-bedded to massive and yielding the characteristic serrated profile.

At the Soo Drawbridge, in northern Washington County, 125 miles northwest of Dresbach, Minnesota, the Jordan is much reduced in thickness and yet it continues to exhibit the usual characteristics which have marked it in other localities. In addition to its remarkable similarity, especially in the lower part, to the beds outcropping at the type locality, this section is notable for the fine development of flat-pebble conglomerates in the Jordan. Near by is the most extensive block faulting known in that county, the maximum displacement being nearly 500 feet. See Table IV.

[1] F. W. Sardeson, *Bull. Minn. Acad. Nat. Sci.*, Vol. IV (1896), pp. 98, 100.

TABLE III

SECTION AT DRESBACH, MINNESOTA

	Feet and Inches
16. Soil and mantle rock	5 7
New Richmond sandstone:	
15. Sandstone, brown to reddish, some white beds or patches; rather coarse-grained, some beds hard like quartzite	22 4
Oneota dolomite:	
14. Limestone, dolomitic, rough, rusty, cherty, with fossils fairly abundant, good collecting along the road westward from town	23 0
13. Limestone, dolomitic, massive gray to drab	44 8
12. Limestone, dolomitic, even-bedded, massive gray to buff in color. This portion is well shown in the old quarry along the road	55 10
11. Limestone, arenaceous, dolomitic, hard, gray to bluish in color. It occurs in 4- to 18-inch layers	27 11
Jordan sandstone:	
10. Sandstone, white to yellowish, medium- to fine-grained, calcite cleavage faces show in sand, some layers resist weathering more than others	17 0
9. Sandstone, massive, yellowish to brown, coarse, cross-bedded	28 4
8. Sandstone, massive, white to yellowish. Some hard layers stand out in relief on face of cliff, others poorly cemented	89 0
7. Sandstone, partly covered	17 0
St. Lawrence formation:	
6. Dolomite, impure, shaly, and shaly green sand. These beds are poorly exposed, usually fossiliferous	138 8
Franconia sandstone:	
5. Sandstone, massive, yellowish to white, medium- to fine-grained with occasional shaly partings. *Dicelomus politus* abundant in certain layers	102 0
Dresbach formation:	
4. Sandstone, often massive but usually sandy shales	28 0
3. Sandstone, massive, white to yellowish or brown. *Dicelomus politus* and *Hyolithes primordialis* common	19 8
2. Sandstone, massive, gray to white or yellowish to buff and brown. These beds are well shown in the old quarry and are very fossiliferous. The common forms include *Dicelomus politus*, *Hyolithes primordialis*, *Lingulella ampla*, and numerous trilobite fragments	18 0
1. Sandstone and sandy shale alternating, white to bluish in color, often cross-bedded. The shaly beds sometimes show mud-cracks and other evidence of shallow-water deposition. These beds are well exposed along the river bank or in the lower quarry and may even be seen below the Mississippi River level at which the section starts. They are highly fossiliferous and contain the same forms mentioned above	22 6

TABLE IV

SECTION AT THE SOO DRAWBRIDGE, NORTHERN WASHINGTON COUNTY, MINNESOTA

	Feet and Inches
Pleistocene:	
18. Wisconsin drift	65 0
Shakopee dolomite:	
17. Limestone, dolomitic, arenaceous, buff, contains *cryptozoon*	2 0
New Richmond sandstone:	
16. Sandstone, coarse, brown	1 0
Oneota dolomite:	
15. Limestone, dolomitic, pink to gray, bedding irregular	85 0
14. Limestone, dolomitic, gray to buff, even-bedded, small quartz geodes occur, also some fossils	11 0
13. Limestone, dolomitic, arenaceous, buff to gray, mostly in thin, irregular beds	5 0
12. Conglomerate, rounded pebbles of well-cemented sandstone imbedded in an arenaceous dolomite	1 0
Jordan sandstone:	
11. Sandstone, massive, hard, white, ripple-marked	1 6
10. Sandstone, coarse, white to buff, containing flat sandstone pebbles	1 6
9. Sandstone, massive, coarse, white to brown, weathered surface often case-hardened, cross-bedding common. A thin seam of gray to greenish clay occurs at the base	13 6
8. Sandstone, medium-grained, massive, white to brown becoming a real flat-pebble conglomerate in the base. Scattered sandstone pebbles are to be found throughout. Base irregular	5 6
7. Sandstone, fine-grained, friable, white. Flat-pebble conglomerate well developed at base. Some fragmentary trilobites occur in these beds	6 0
6. Sandstone, massive, brown, hard	3 6
5. Sandstone, massive, white, poorly cemented, fine-grained. Cross-bedding and color-banding common. A few flat sandstone pebbles at the base	27 6
4. Sandstone, massive, white to yellowish brown, fine-grained and somewhat color-banded	12 0
3. Conglomerate, flat pebbles of sandstone imbedded in the sand matrix	1 0
St. Lawrence formation:	
2. Shale, arenaceous, buff to bluish, with blue clay partings. Some small brachiopods occur in these beds, but they are mostly fragmentary	5 6
1. Shale, dolomitic, sandy, gray to buff, with thin layers of argillaceous blue shale. To level of St. Croix River	25 0

A similar section of the Jordan sandstone is exposed at Osceola, Wisconsin, 4 miles to the northeast; even the color-banding displayed in the lower part of the formation at the Soo Drawbridge and at the type section in Jordan is common.

FAUNA

Most Paleozoic formations that occur as very pure loose quartz sands are but sparingly fossiliferous, and such is the case with the Jordan. If these beds were ever well cemented or abundantly fossiliferous it is quite probable that the copious water which the formation yields has long since carried away in solution both the cement and the calcareous shells, especially in the coarser upper portion. The cement of these beds, as they occur now, is obviously secondary. It is quite in line with expectation, then, to find that fossils are rare in the Jordan sandstone. However, they have been found in some abundance near the middle of the formation. One of these places is along the highway about 3 miles northeast of Stillwater where they occur about 40 feet below the base of the Oneota dolomite.[1] Another place is 1 mile north of Marine where they occur 75–88 feet above the top of the St. Lawrence formation,[2] and at the Soo Drawbridge in northern Washington County where they occur within 24 feet of the base of the Oneota. At Osceola, Wisconsin, the same fauna occurs in the sandstone in the old quarries at the north edge of the village. At this latter place the fossiliferous layers occur about 140 feet above the river, or 35 feet below the base of the Oneota as exposed at Eagle Cliff near the village water tower. Some of the more common of the fossils occurring in the Jordan are apparently:

Billingsella coloradoensis (Shumard)
Finkelnburgia osceola (Walcott)
Holopea sweeti Whitfield
Osecolia osceola (Hall)
Dikellocephalus limbatus Hall
Illaenurus quadratus Hall
Saukia leucosia Walcott
S. pepinensis (Owen)
S. pyrene Walcott

[1] Eunice Peterson, unpublished notes.

[2] Eunice Peterson, *The Cambrian Geology of the Lower St. Croix Valley* (unpublished thesis on file at the University of Minnesota, 1924), p. 29.

In fact, it is undoubtedly the same fauna as that E. O. Ulrich finds in the portion of the Jordan which he has recently cut off to form a new member of his expanded Trempealeau formation and which he calls the Norwalk sandstone.[1] Unfortunately, these are the very beds outcropping at the type locality, and, although few fossils have been found in them at Jordan, the deposit is much more typical Jordan sandstone than the upper or massive beds that have been removed by erosion at the place where the type section was measured, and which are sometimes mentioned as if characteristic.

In the Minnesota Valley fossils occur but rarely in the Jordan. Two rather fragmentary brachiopods, one probably an *Obolus* and the other a *Lingulella*, were found at Jordan about 50 feet above the top of the St. Lawrence formation. Near the top of what has usually been called Jordan at various places along the Minnesota River, such as St. Peter and Kasota, great numbers of gastropods occur. These are mostly Raphistomas, and belong to several different species, but there are also one or two undoubted Ophiletas as well. This is the general locality (Traverse des Sioux) and the horizon from which B. F. Shumard collected his types of *Raphistoma minnesotensis*[2] and with which he also found the pygidium of a small trilobite. If this fauna, occurring in the sandstone at Kasota and adjacent localities, be classed as Ordovician, where it seems to belong, there remain only the few fragments of brachiopods from the sandstone of the type locality and the dozen or so species of brachiopods, gastropods, and trilobites found rather sparingly along the St. Croix River which can be claimed as the Jordan fauna, although E. O. Ulrich has collected a rather extensive fauna from it in Wisconsin. While these forms may be more or less limited to this horizon,[3] they resemble so closely similar ones occurring at lower horizons that they are often considered identical with them. Of a collection of supposedly Jordan fossils from the vicinity of Devil's Lake, Wisconsin, C. D. Walcott says: "The fauna is of the same general facies as that of the upper portion of the St. Lawrence formation, but the trilobites differ in minor details."[4] Relationships somewhat similar to

[1] *Trans. Wis. Acad. Sci. Arts and Letters*, Vol. XXI (1924), pp. 83–86.

[2] Owen, *op. cit.*, p. 484.

[3] Ulrich, *op. cit.*, p. 86.

[4] *Smithsonian Miscellaneous Collections*, Vol. LVII (1914), p. 355.

this are common to the greater part of the St. Croixan series. Thus, about 20 per cent of the St. Lawrence species occur in the Franconia and 12 per cent of the same species are also found in the Dresbach.

CONCLUSION

The Jordan, as described by N. H. Winchell, is a fine, medium- to coarse-grained sandstone although the coarse, massive upper beds belonging to the formation do not outcrop at the type locality. The formation has been adequately described and its limits definitely established. Some confusion of formations hampered the early use of the name, but this was merely an erroneous identification of formations and did not affect the original definition or limitations of the Jordan sandstone. N. H. Winchell was able to establish the true relationship of the formations in question and corrected the false correlations himself.

The sandstone layers carrying the *Raphistoma* and *Ophileta* fauna, as found in the vicinity of St. Peter and southward along the Minnesota Valley, have probably been worked over after their original deposition and should be included with the Oneota. In many places the fauna of the Jordan is much limited and in many more it is absent, but in some places it is quite abundant, even within 25 feet of the base of the Oneota, and it consists of typical St. Croixan forms. The beds carrying this fauna are those which E. O. Ulrich would cut off and add to his expanded Trempealeau formation as the Norwalk sandstone member. This, however, would limit the Jordan to beds which do not outcrop at the type locality and therefore displace the name. In view of the general usage of the name Jordan and its priority, it is doubtful whether it would be wise to make the substitution, hence the retention of the Jordan, as originally defined and as used for many years, is strongly urged.

STUDIES IN THE FELDSPAR GROUP

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ABSTRACT

Soda feldspar is believed to crystallize in three different phases having definite relationships with the three crystal phases of potash feldspar; the relations between composition and optic properties in these three series are shown in three diagrams, and those between adularia and celsian in a fourth. Finally, another diagram shows the classifications of plagioclase proposed by various authorities, together with a modification suggested by the writer.

An accurate understanding of the relations between optical characters and chemical composition in the feldspar group is a fundamental necessity for successful work in microscopic petrography. Therefore, the remarkable diagrams of Michel Lévy[1] have been of inestimable service to petrographers. However, these diagrams relate only to a single sample of microcline of fixed composition, and to the plagioclase series, which is assumed to be composed solely of albite ($NaAlSi_3O_8$) and anorthite ($CaAl_2Si_2O_8$). Analyses of microcline suggest that it varies in composition from the pure end-member, $KAlSi_3O_8$, to types containing nearly 40 per cent[2] of $NaAlSi_3O_8$, to say nothing of minor amounts of other molecules, such as $CaAl_2Si_2O_8$. Also, natural plagioclase is only very rarely composed solely of albite and anorthite but nearly always contains 3–10 per cent of $KAlSi_3O_8$, besides minor amounts of other molecules, such as $Na_2Al_2Si_2O_8$, $BaAl_2Si_2O_8$, etc. It is evident that a strictly correct and complete presentation of the relations between optic characters and composition must take account of all these constituents. Such a presentation in graphic form is impossible for several reasons, but the time is approaching when feldspars will be dealt with in terms of

[1] A. Michel Lévy, *Étude sur la Détermination des Feldspaths*. Paris, 1894, 1896, and 1904.

[2] However, carefully studied samples very rich in $NaAlSi_3O_8$ are perthitic intergrowths in all cases; the writer has found no data which show clearly the maximum amount of $NaAlSi_3O_8$ in microcline, but would estimate it at about 20 per cent.

three components, instead of one or two, as in the past. The need of such a procedure is well shown by the graphic tabulation of nearly a thousand analyses of feldspars, prepared by Alling.[1] This diagram shows the results of calculating all available satisfactory feldspar analyses into their three chief constituents, namely, $KAlSi_3O_8$, $NaAlSi_3O_8$, and $CaAl_2Si_2O_8$. The diagram makes very plain the fact that plagioclase is a continuous series, chiefly, but not wholly, composed of $NaAlSi_3O_8$ and $CaAl_2Si_2O_8$, and that another apparently continuous series exists, composed chiefly, but not wholly, of $KAlSi_3O_8$ and $NaAlSi_3O_8$. Alling[2] has likewise prepared very interesting diagrams of the chief optic characters of feldspars showing their relations to the three chief components of the group. His is pioneer work along this line, which should prove of much importance.

It is the purpose of this article to discuss in some detail the relations between optic properties and composition in the apparently continuous series between $KAlSi_3O_8$ and $NaAlSi_3O_8$; to this discussion will be added a brief study of the $KAlSi_3O_8$–$BaAl_2Si_2O_8$ series, and notes on the classification of the plagioclase series. The study of two-component series by means of graphs is much simpler than that of three-component systems, and it is in the hope that such a study of the alkaline feldspars will contribute materially to our knowledge of the three-component system whose constituents together make up at least 95 per cent of nearly all feldspars that this paper has been prepared.

1. THE ALKALINE FELDSPAR SERIES

In the plagioclases there is no longer any doubt concerning the continuity of the series, and each end-member has only one well-known modification;[3] but in the alkaline feldspar series there is much doubt regarding continuity, and $KAlSi_3O_8$ has at least two, and perhaps three, crystal modifications. These facts increase very considerably the difficulties involved in developing a correct presentation of

[1] *Jour. Geol.*, Vol. XXIX (1921), p. 193, Fig. 19.

[2] *Ibid.*, p. 250; Vol. XXXI (1923), pp. 361, 366.

[3] According to Merwin (*Jour. Wash. Acad. Sci.*, Vol. I [1911], p. 59), albite inverts at about 900° C. to a high-temperature form, but such a form is unknown in rocks.

the relations between optic characters and composition in this series.

Potassium feldspar ($KAlSi_3O_8$) crystallizes at high temperature to a monoclinic form first shown by Des Cloizeaux to be different optically from ordinary orthoclase and called by him "abnormal orthoclase" (*orthose déformé*). However, the glassy potassium feldspar of volcanic rocks has long been known as "sanidine," and, since this feldspar is almost invariably the high-temperature type, it seems proper to adopt sanidine as the name of that crystal phase of potassium feldspar stable at high temperature. In plutonic rocks, potassium feldspar is found in a different crystal state known as ordinary orthoclase, or adularia, which probably formed at lower temperature. Adularia inverts to sanidine on heating to about 900° C., according to Merwin,[1] but the change is very sluggish in dry heat and Kozu found no inversion to sanidine up to 1,100° C. in moonstone from Ceylon and also in moonstone from Korea. The reverse change does not take place easily, but may occur with very slow cooling. According to Bücking,[2] pressure parallel to *b* causes the same changes in the optic angle of orthoclase as moderate increase of temperature. According to Alling,[3] shearing stresses at low temperature tend to cause orthoclase to change to a twinned condition known as microcline, but this needs further proof.

There has been much discussion concerning the relations between orthoclase and microcline. Many writers regard them as essentially identical, differing only in the coarseness of twinning, which is microscopically visible in microcline and considered to be present submicroscopically in orthoclase. Michel Lévy[4] has shown that, within the limits of error, the extinction angles in 001 in adularia would be a necessary consequence of such submicroscopic twinning of microcline units. However, the most accurate measurements of specific gravity, refractive indices, and optic axial angle seem to indicate slight differences between orthoclase and microcline, and the observation of Merwin that orthoclase inverts at about 900° C., while microcline is stable to its melting-point, seems to show that the two are not identical, in spite of the fact that X-ray studies show no

[1] *Loc. cit.* [2] *Zeit. Kryst.*, Vol. VII, p. 566.

[3] *Op. cit.*, Vol. XXIX (1921), pp. 209, 275.

[4] *Bull. Soc. Fr. Min.*, Vol. II (1879), p. 135.

differences[1] between them. It may be added that the negative results with X-rays are not convincing in view of the fact that Kozu and Endo[2] found no differences between the X-ray pattern of adularia at ordinary temperature, and from the same crystal, after heating more than an hour at 1,060° C. and quenching, which process must have converted it into sanidine (according to the results of Des Cloizeaux and Merwin).

Sodium feldspar ($NaAlSi_3O_8$) is generally regarded as having only one crystal form, namely, albite. However, Merwin[3] has shown that albite crystals invert at about 900° C. to a different modification, whose properties have not been determined. Furthermore, nearly pure $NaAlSi_3O_8$ (with about 10 per cent $KAlSi_3O_8$) crystallizes in a pseudo-monoclinic form, which has been called "anorthoclase." Therefore, there seem to be three crystal modifications of $NaAlSi_3O_8$, just as there are three forms of $KAlSi_3O_8$, namely, the high-temperature form, ordinary albite, and the so-called "anorthoclase."

This name, "anorthoclase," like the rock-name, "anorthosite," is a very unfortunate selection. The name was given because the mineral is microscopically somewhat like, but distinguishable from, orthoclase. Except in the rare case of the absence of twinning, the mineral in thin section is, however, much more like microcline than like orthoclase. Furthermore, the name suggests a close chemical relationship to orthoclase, whereas the mineral grades from a near-identity with albite to a composition about half-albite and half-orthoclase. In the writer's opinion, "analbite" would be a much better name for this mineral than "anorthoclase," but such a change of nomenclature is so difficult and improbable that he would propose, merely, that so-called "anorthoclase," which contains less than 10 molecular per cent of $KAlSi_3O_8$, should be called "analbite." Such samples of anorthoclase have been called "abnormal albite" by Dana.[4]

Since there are three crystal phases of $KAlSi_3O_8$ and probably

[1] Hadding, *Lund's Univ. Aarskr.*, Vol. XVII (1921); quoted by J. H. L. Vogt (*Jour. Geol.*, Vol. XXXI [1923], p. 411) as conclusive evidence that orthoclase and microcline are identical.

[2] *Sci. Rep. Tohoku Imp. Univ.*, Vol. I (3d ser., 1921), p. 10.

[3] *Loc. cit.*

[4] *System of Mineralogy* (1892), p. 330.

also of $NaAlSi_3O_8$, one might expect to find three modifications of anorthoclase (in the restricted sense just defined). However, potassium-bearing albites are very rare, and in the few cases known the percentage of potassa is quite low. That is, so far as now known, there is no analogue of anorthoclase in the adularia-albite (discontinuous) series. On the other hand, so-called "monoclinic anorthoclase" has been described repeatedly,[1] and Angel[2] has studied a somewhat more potassic type, which he called "natronsanidine." It seems clear, therefore, that there are two phases of $(Na,K)AlSi_3O_8$, one being monoclinic and stable at high temperature, while the other is triclinic and stable (or metastable) at low temperature. That $NaAlSi_3O_8$ has a monoclinic form like that of orthoclase is shown by the results obtained by Kozu[3] (with Endo and Suzuki) in an X-ray study of moonstone (a soda-bearing variety of adularia showing schillerization) and normal adularia. The former gave a double set of spots in the Laue photograph, one set being identical with that of normal adularia and the other set having the same symmetry, but being differently spaced at ordinary temperature; above 575° C. the second set moved toward the first set, becoming coincident with it at 800°–1,050° C. This change may be related to the inversion of albite at 900° C. found by Merwin.

The properties of the high-temperature form of $NaAlSi_3O_8$ have not been determined, but it has been shown that it is probably monoclinic and closely related to sanidine. It forms the end-member of a series, $KAlSi_3O_8$–$NaAlSi_3O_8$, which Mäkinen[4] has shown to be continuous, and which is believed to be monoclinic throughout. The monoclinic form of $NaAlSi_3O_8$ was named "barbierite" by Schaller,[5] because Barbier[6] first called attention to it.

[1] The latest example is in an article by H. S. Washington, *Amer. Jour. Sci.*, Vol. CCVI (1923), p. 107; Washington calls the mineral merely "alkali feldspar."

[2] *N. Jahrb. Mineral. Beil. Bd.*, Vol. XXX (1910), p. 254.

[3] *Sci. Rep. Tohoku Imp. Univ.*, Vol. III, No. 1 (1921), pp. 1 and 19.

[4] *Geol. För. Förh. Stockholm*, Vol. XXXIX (1917), p. 121.

[5] *Bull. Soc. Fr. Min.*, Vol. XXXIII (1910), p. 320; *Zeit. Kryst.*, Vol. L (1911), p. 347; *Jour. Wash. Acad. Sci.*, Vol. I (1911), p. 177; and *U. S. Geol. Surv. Bull. 509* (1912), p. 40.

[6] *Bull. Soc. Chim. Fr.*, Vol. III (1908), p. 894; *Bull. Soc. Min. Fr.*, Vol. XXXIII (1910), p. 81.

The alkaline feldspars are therefore believed to belong to three series, namely:

1. Sanidine—barbierite; monoclinic and continuous; stable only at high temperature (above 900° C.); sanidine is metastable and barbierite unstable at ordinary temperature.
2. Adularia—albite; monoclinic and triclinic and discontinuous.
3. Microcline—analbite; triclinic and discontinuous.

The stability relations between the second and third series are not yet established; pressure or shearing may be of importance.

The gap, or discontinuity, in the second series extends from about $Or_{70}Ab_{30}$ to about $Or_{10}Ab_{90}$. The gap in the third series is commonly regarded as still greater, but according to data collected for this study it is much less, namely, from about $Or_{80}Ab_{20}$ to about $Or_{40}Ab_{60}$. A smaller gap in this series may be due to the fact that the two end-members are both triclinic, while in the second series one is monoclinic and the other is triclinic.

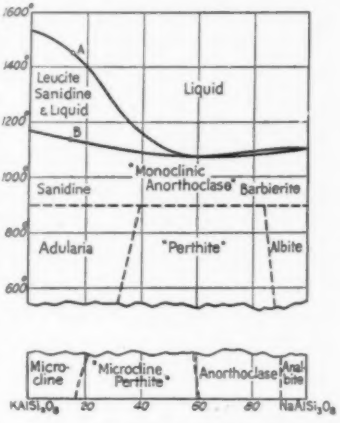

FIG. 1.—Temperature-composition diagram for alkaline feldspars.

The stability relations of the alkaline feldspars, according to these views, are shown graphically in Figure 1, in which the points *A* and *B* and the incongruent melting of $KAlSi_3O_8$ with formation of leucite are according to Morey and Bowen,[1] the melting-point of $NaAlSi_3O_8$ is that given by Bowen,[2] the minimum melting temperature between $KAlSi_3O_8$ and $NaAlSi_3O_8$ is according to Dittler,[3] the inversion temperature at 900° C. for both substances is that given by Merwin,[4] and the composition stability limits of adularia, albite, microcline, and anorthoclase are as estimated in this article. The break between adularia and microcline and between albite and analbite-anorthoclase is not in-

[1] *Amer. Jour. Sci.*, Vol. CCIV (1922), p. 1. [2] *Ibid.*, Vol. CLXXXV (1913), p. 577.
[3] *Tsch. Min. Pet. Mitth.*, Vol. XXXI, 1912.
[4] *Loc. cit.*

tended to indicate any definite temperature (since pressure or shearing may be more important than temperature in this case), but merely to express the writer's view that all these phases exist and are not equivalent. More explicitly, it is believed that pure $NaAlSi_3O_8$ crystallizes from the melt to a high-temperature form (which is probably monoclinic barbierite), and this inverts, even when cooled very quickly, to albite, the latter being stable at all temperatures, though only a small tenor of $KAlSi_3O_8$ is required to cause inversion under unknown conditions to analbite. Further, $Or_{30}Ab_{70}$ crystallizes from a melt at about 1065° C., and when completely crystallized it is monoclinic anorthoclase of the same composition; at 900° C. this becomes unstable but may either separate into two phases or (especially if cooled quickly) change to (ordinary triclinic) anorthoclase, which is stable or metastable at ordinary temperature. Finally, pure $KAlSi_3O_8$ crystallizes to leucite and sanidine, and later to sanidine alone, which is stable to 900° C. and metastable to 0° C.; below 900° C. it tends to invert to adularia, and this form may change to microcline under unknown conditions. On account of dissociation of $KAlSi_3O_8$, the relations shown in Figure 1 belong on a ternary diagram, and in the area between the curves *A* and *B* all the facts are not shown.

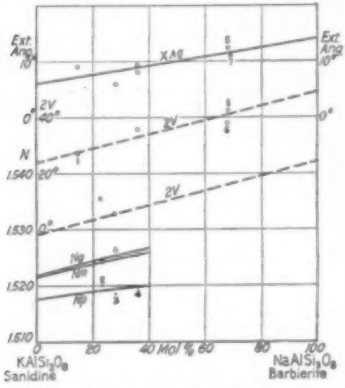

FIG. 2.—Variations in optic properties and composition in the sanidine-barbierite series.

The relations between optic properties and composition in the sanidine-barbierite series are shown in Figure 2, so far as data permit. No data are available regarding barbierite, and the only data so far discovered for monoclinic orthoclase are two records by Förstner,[1] which are inconsistent and probably both inaccurate so far as indices of refraction are concerned. Data are also lacking for pure sanidine.

[1] *Zeit. Kryst.*, Vol. VIII (1884), p. 125.

It will be noted that two lines are given for the value of the optic angle ($2V$); they express the fact that there is a wide variation in $2V$ in this series, probably due to incomplete inversion to (or from) adularia. When the latter is heated, the optic angle decreases steadily, becoming 0° at 600° to 800° C., and then opening out in 010 at right angles to its previous position. At about 900° C., as determined by Merwin, the mineral inverts to sanidine. If the temperature does not reach 600° C., the change is reversed on cooling, according to Des Cloizeaux, and the final condition is about the same as at first. However, if the temperature passes 600° C., the change is not easily reversed, and the condition obtained by heating may remain with little change on cooling. In this way the optic angle may be of almost any value (less than 70°—the angle in adularia) in the plane normal to 010, and from 0° to about 20° in 010. Such variations are not uncommon in natural orthoclase. In true sanidine (with no partial inversion) the optic angle would probably belong on a line somewhat below the lower $2V$-line of the figure. Therefore, the optic angle should not be used to determine the composition, but only to distinguish between adularia and sanidine. The extinction angle in 010 may then be used to give the composition. The line of this extinction angle corresponds fairly well with the data for "glassy feldspar" collected and graphed by Johansson (see N. H. Magnusson, *Geol. För. Förh.*, Vol. XLV, 1923, p. 308).

REFERENCES FOR THE SANIDINE-BARBIERITE SERIES

1. "Orthoclase," Laachersee. R. Brauns, *N. Jahrb. Mineral. B. B.*, Vol. LXVI (1921), p. 1.
2. "Sanidine," Eifel. S. Kozu and Y. Endo, *Sci. Rep. Tohoku Imp. Univ.*, Vol. III, No. 1 (1921), p. 1.
3. "Orthoclase," Wehr. A. des Cloizeaux, *Man. Minéral.*, Vol. I (1862), p. 332. Analysis by J. Lemberg, *Zeit. d. geol. Gesell.*, Vol. XXXV (1883), p. 603.
4. "Moonstone," Sankori, Korea. S. Kozu and Y. Endo, *loc. cit.* Extinction angle on 010=$X:a=9°-10°$ (personal communication, Nov. 8, 1923).
5. "Soda-orthoclase," Cala Porticello, Pantellaria. H. Förstner, *Zeit. Kryst.*, Vol. VIII (1884), p. 125.
6. "Soda-orthoclase," Bagno dell'acqua, Pantellaria. H. Förstner, *loc. cit.*
7. "Feldspar," Kilimanjaro. L. Fletcher and H. A. Miers, *Min. Mag.*, Vol. VIII(1887), p. 131.

The relations between optic properties and composition in the discontinuous adularia-albite series are shown in Figure 3. A line for specific gravity is added. The data for this diagram are scanty, and accuracy cannot be claimed for it.

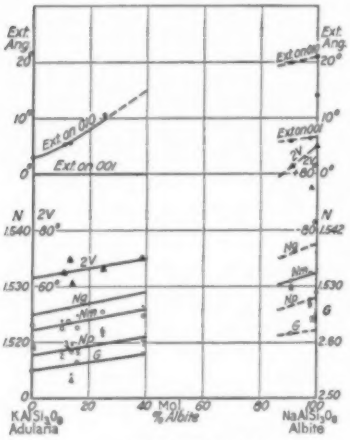

FIG. 3.—Variations in optic properties and composition in the adularia-albite series.

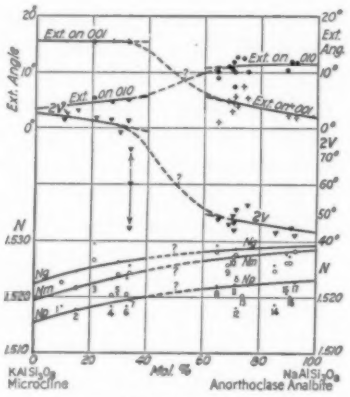

FIG. 4.—Variations in optic properties and composition in the microcline-analbite series.

REFERENCES FOR THE ADULARIA-ALBITE SERIES

1. Artificial, pure adularia. J. Koenigsberger and W. J. Müller, *N.J.B.B.*, Vol. XLIV (1921), p. 402.
2. Adularia, St. Gotthard. S. Kozu, *Sci. Rep. Tohoku Imp. Univ.*, Vol. III, No. 1 (1921), p. 1. Extinction angle on 010 = 5.5° (personal communication, Nov. 8, 1923).
3. Adularia, St. Gotthard. A. des Cloizeaux, *Man. Minéral.*, Vol. I (1862), p. 331.
4. Adularia, St. Gotthard. S. Kozu, *loc. cit.;* also *Min. Mag.*, Vol. XVII (1916), p. 253, and *Bull. Soc. Min. Fr.*, Vol. LX (1917), p. 36.
5. Adularia, St. Gotthard. D. S. Byelyankin, *Bull. Petrograd Polytech. Inst.*, Vol. XXIV (1916), p. 437, through *Min. Abst.*, Vol. I (1920), p. 89.
6. "Moonstone," Ceylon. S. Kozu, *loc. cit.* Extinction angle on 010 = 10°–11° (personal communication, Nov 8, 1923)
7. Adularia Ceylon. D. S. Byelyankin *loc. cit.*
8. "Moonstone." Mineral Hill, Pa. O. Anderson, *Amer. Jour. Sci.*, Vol. CXC (1915), p. 382. Analysis by A Leeds, *Amer. Jour. Sci.* Vol. CVI (1873), p. 25.

9. Albite, Kramkogel, Rauris, Salzburg. C. Viola, *Zeit. Kryst.*, Vol. XXXII, p. 328.
10. Albite, pure. F. E. Wright, *Amer. Jour. Sci.*, Vol. CLXXXVI, 1913.

The relations between optic properties and composition in the discontinuous microcline-anorthoclase-analbite series are shown in Figure 4. The optic angle ($2V$) line is particularly disjointed, as if the two parts did not belong to any single curve, and yet Byelyankin describes in zones of a single crystal (No. 7) a variation of the optic angle from 44° to 72°, which completely bridges the gap and indicates that the curved lines, rather than the discontinuous ones, are correct.

All the data of Figures 2–4 have been plotted only after introducing corrections, so far as possible, for minor amounts of anorthite, and various other molecules; these corrections affect both the indicated composition and also the optic properties.

REFERENCES FOR THE MICROCLINE-ANALBITE SERIES

1. Microcline, Antaboko, Madagascar. Duparc, Wunder, and Sabot, *Mem. Soc. phys. Hist. nat. Genève*, Vol. XXXVI (1910), p. 365.
2. Microcline, Antsongombato, Madagascar. Duparc, Wunder, and Sabot, *op. cit.*, p. 363.
3. Microcline, Gasern bei Meissen. N. J. Ussing, *Zeit. Kryst.*, Vol. XVIII (1891), p. 192.
4. Microcline, Tammela, Finland. E. Mäkinen, *Bull. Com. Géol. Finlande*, Vol. XXXV (1913), p. 58.
5. Microcline, Savelev ravine, Ilmen Mts. D. S. Byelyankin, *Bull. Petrograd Polytech. Inst.*, Vol. XXIV (1916), p. 437. Through *Min. Abst.*, Vol. I (1920), p. 89.
6. Microcline, Tammela, Finland. E. Mäkinen, *loc. cit.*
7. "Anorthoclase," Chu river, Turkestan. D. S. Byelyankin, *Bull. Petrograd Polytech. Inst.*, Vol. XXVI (1918), p. 83. Through *Min. Abst.*, Vol. II (1923), p. 75.
8. Anorthoclase, Porto Scuso, Sardinia. C. Riva, *Zeit. Kryst.*, Vol. XXXV (1901), p. 274. Also F. Fouqué, *Bull. Soc. Min. Fr.*, Vol. XVII (1894), p. 283.
9. Anorthoclase, S. Marco, Pantellaria. H. Förstner, *Zeit. Kryst.*, Vol. VIII (1884), p. 129.
10. Anorthoclase, Khania, Pantellaria. H. Förstner, *loc. cit.*
11. Anorthoclase, Berkum, Rhine. D. S. Byelyankin, *Bull. Petrograd Polytech. Inst.*, Vol. XXIV (1916), p. 437. Through *Min. Abst.*, Vol. I (1920), p. 89.
12. Anorthoclase, Vidalenc, Mont Dore. F. Fouqué, *op. cit.*, p. 415.
13. Anorthoclase, Zichidi, Pantellaria. H. Förstner, *op. cit.*, p. 126.
14. Anorthoclase, Quatre Ribeiras, Azores. F. Fouqué, *op. cit.*, p. 397, and Vol. VI (1883), p. 197.

15. Anorthoclase, Castello Branco, Fayal. F. Fouqué, *ibid.*, p. 401.
16. Anorthoclase, Quatre Ribeiras, Azores. F. Fouqué, *ibid.*, p. 397.
17. Anorthoclase, Grande Caldeira, Azores. F. Fouqué, *ibid.*, p. 401.

2. THE POTASSIUM-BARIUM FELDSPAR SERIES

Barium feldspar ($BaAl_2Si_2O_8$), although chemically so closely similar to calcium feldspar ($CaAl_2Si_2O_8$), is monoclinic and isomorphous with orthoclase ($KAlSi_3O_8$), with which it seems to be miscible in all proportions, while it enters into crystal solution in plagioclase only in very minor amounts. The mutual crystal solutions of barium and potassium feldspars rich in potassium known as hyalophanite are barium-bearing adularia, as can be seen very easily from the graph (Fig. 5) of the relations between optic characters and composition in this series. However, it is still uncertain whether the pure barium feldspar, celsian, is related in the same way to adularia, or to sanidine. If the relationship is to adularia, as seems probable, the diagram of optic properties and composition must be about as shown in Figure 5, but if it is to sanidine, then celsian and hyalophanite do not belong to the same series, and the relations between celsian and sanidine remain to be determined.

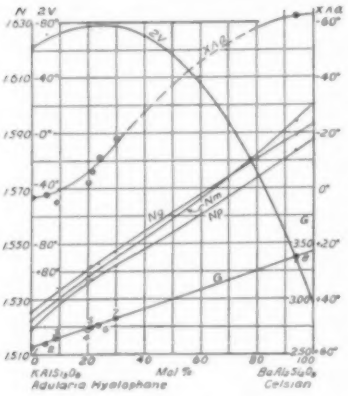

FIG. 5.—Variations in optic properties and composition in the adularia-celsian series.

Since intermediate types are known only from pure orthoclase to 70 per cent orthoclase–30 per cent celsian, it may be worth while to explain the derivation of the diagram (Fig. 5). It is incorrect to show the line for $2V$ from $-62°$ for orthoclase through 90° (change of sign) to $+86°$ for celsian, as doubtfully suggested by the dotted line in Figure 94, page 200, of Winchell's *Optical Mineralogy*, since the optic plane in celsian is at right angles to its position in adularia, and the only way the optic plane can change position with respect to the 010 plane (except in triclinic crystals) is by a simultaneous passage of the $2V$ curve through 0°. Since adularia and celsian differ

both in optic sign and in the position of the optic plane, the curve of $2V$ must pass through 90° and also through 0° between the two, assuming that the isomorphous series is continuous. Also, the $2V$-curve must turn, as shown, and pass through 0° before passing through 90°, since for the ray vibrating parallel with b in adularia and hyalophanite these minerals have the highest index, N_g, while celsian has the intermediate index, N_m, for the same ray; that is, as shown in Figure 5, N_g of adularia and hyalophanite must become N_m of celsian, which requires that the $2V$-curve shall pass through $-0°$ rather than through $+0°$. In other words, the sign of the mineral having $2V=0°$ must be negative and not positive.

The indices of refraction reported by Eskola[1] for pure, artificial barium feldspar suggest a negative sign, but Merwin[2] reports that Eskola's material gives interference figures which are "decidedly positive," the optic angle ($2V$) being estimated at 60°–80°. This is in agreement with the results of Strandmark[3] and Tacconi[4] on natural celsian; the latter gives the value: $(+)2V=71°\ 58'$. In the diagram the value of Strandmark[5] is used for 94 per cent pure celsian.

REFERENCES FOR THE ADULARIA-CELSIAN SERIES

1. Pure, artificial adularia. J. Koenigsberger and W. J. Müller, *N.J.B.B.*, Vol. XLIV (1921), p. 402.
2. J. E. Strandmark, *Geol. För. Förh. Stockholm*, Vol. XXV (1903), p. 289, and Vol. XXVI (1904), p. 97.
3. H. Baumhauer, *Zeit. Kryst.*, Vol. XXXVII (1903), p. 605.
4.–8. J. E. Strandmark: *loc. cit.*

3. THE CLASSIFICATION OF PLAGIOCLASE FELDSPARS

Those who study minerals are accustomed to regard them as (elements or) compounds of definite chemical composition corresponding with some (more or less) simple chemical formula; therefore, even after the gradual acceptance of Tschermak's idea that albite and

[1] *Amer. Jour. Sci.*, Vol. CCIV (1922), p. 366.

[2] Personal communication, Nov. 20, 1923.

[3] *Geol. För Förh. Stockholm*, Vol. XXV (1903), p. 289, and Vol. XXVI (1904), p. 97.

[4] *Zeit. Kryst.*, Vol. XLIII (1905), p. 424, and Vol. LIV (1914), p. 388.

[5] Strandmark's data have been repeatedly assigned to pure $BaAl_2Si_2O_8$; his analysis gives only 89 per cent Cn, but excluding Ca, Mg, and Mn it is 94 per cent Cn, as given in Fig. 5.

anorthite are miscible in all proportions in plagioclase, mineralogists have thought and written of triclinic feldspars in terms of various definite amounts of the end-compounds in simple ratios. This fact is responsible for much of the confusion regarding the classification of plagioclase. Such a practice is clearly not in harmony with the composition of natural feldspars, since it implies that the usual plagioclase crystal is composed of albite and anorthite in some simple ratio, whereas actual analyses show that simple ratios are mere accidents, and all possible ratios exist. Accordingly, it is here proposed to use simple ratios, not as characteristic of the types, but as the limits of types. This is not a new proposal, but is merely reverting to the plan proposed by Tschermak, which, in this respect, has rarely been followed, even by those accepting his theory and presumably using his classification. The usual procedure has been to specify that certain simple ratios belong to certain types (thus, Ab_3An_2, Ab_4An_3, and Ab_1An_1 to andesine), a practice which is unfortunate not only because it implies that simple ratios are to be expected, but also because the limits of the types are not given. This last fact explains the numerous gaps in the diagram (Fig. 6), which are not due to a belief that the series is discontinuous, but to the absence of any statement as to the precise limits between types.

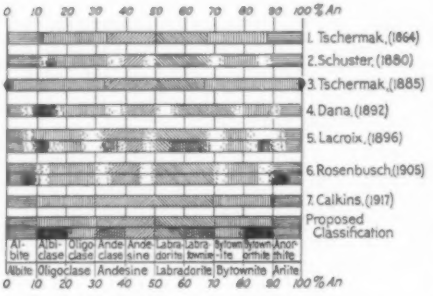

FIG. 6.—Classification of plagioclase

Calkins[1] has recently suggested a modification of Tschermak's original proposal in order to put the divisions at simple numbers on a decimal basis. This is clearly a step in the right direction and has been adopted by Alling,[2] though Johannsen[3] prefers decimal divisions (5, 27.5, 50, 72.5, and 5) which are not simple.

[1] *Jour. Geol.* Vol. XXV (1917), p. 157. Calkins' plan was used in 1914 by Johannsen (*Man. Pet. Methods*, p. 278).

[2] *Ibid.*, Vol. XXIX (1921), p. 217.

[3] *Essentials for the Microscopic Determination of Rock-forming Minerals and Rocks* (1922), p. v and Fig. 24.

There has been a decided tendency during recent years to use compound names like oligoclase-albite to designate more exactly the kind of plagioclase found in various cases. This tendency began forty years ago in the writings of Schuster[1] and is well developed in the works of Lacroix,[2] who employs five such names. It is in the belief that it is desirable to adopt abbreviated forms of such names and to give them definite meaning that the plan presented in Figure 6 has been developed.

REFERENCES FOR THE PLAGIOCLASE SERIES

1. G. Tschermak, *Sitzb. Akad. Wiss. Wien*, Vol. L (1864), p. 566.
2. M. Schuster, *Tsch. Min. Pet. Mit.*, Vol. III (1880), p. 117. Also used by H. Rosenbusch, *Mikro. Phys.*, 2d ed., 1885 ("nach Tschermak").
3. G. Tschermak, *Lehrb. Mineral.* (1885), p. 465. Also used by F. Zirkel, *Lehrb. Petrog.*, Vol. I (2d ed., 1893), p. 220.
4. E. S. Dana, *System of Mineralogy* (6th ed., 1892), p. 327.
5. A. Lacroix, *Minéral. France*, Vol. II (1896), p. 130.
6. H. Rosenbusch, *Mikro. Phys.*, Vol. I, Part 2 (4th ed., 1905), p. 348.
7. F. C. Calkins, *Jour. Geol.*, Vol. XXV (1917), p. 157. Also used by H. A. Alling, *ibid.*, Vol. XXIX (1921), p. 217.

[1] *Tsch. Min. Pet. Milth.*, Vol. III (1880), p. 117.

[2] *Minéral. France*, Vol. II (1896), p. 130.

PRE-KEEWATIN SEDIMENTS OF THE UPPER HARRICANA BASIN, QUEBEC[1]

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Columbia University, New York

ABSTRACT

The Keewatin volcanics of the upper Harricana River consist of femic flows at the base, grading upward into pillow andesites, rhyolites, and tuffs. The basal femic flow overlies and contains inclusions of various members of an older sedimentary series of carbonaceous slate, cross-bedded sandstone, silicated limestone, a quartzite, and greywacke gneiss, having a total thickness of at least 4,000–6,000 feet. The sediments have been intruded by two granites, the earlier of which is cut by the dykes which served as feeders to the Keewatin lavas. The second granite intrudes an outlier of the Cobalt series, found 2 miles south of Amos.

INTRODUCTION

Keewatin volcanic rocks and associated ferruginous bands, usually referred to as "iron formation," were once regarded as the basement upon which the geological floors of North America have been built. Professor A. C. Lawson[2] found a sedimentary series in the Rainy Lake district which he believed to lie unconformably below these ancient volcanics and called it the Coutchiching series. More recently Professor F. F. Grout,[3] by using information not then available, has pointed out that the Coutchiching series may be younger than the volcanics with which it is in contact. If the Coutchiching series is younger than the Keewatin, then it should be possible to find some other more ancient terrain upon which the Keewatin lavas and volcanic tuffs were laid down.

[1] The field work upon which this paper is based was performed for the Geological Survey of Canada and is published with the permission of the director, but without concurrence on all the statements made and opinions expressed by the author.

The writer wishes to make grateful acknowledgment to Professor James F. Kemp for thoughtful criticism, advice, and encouragement, and to Professor R. J. Colony for assistance in studying the thin sections of the silicated limestone.

[2] *C.G.S., Mem. 40*, pp. 27–28.

[3] Paper presented before the Geological Society of America at the annual meeting at Ithaca, 1924.

The ancient basement from which the Keewatin lavas were ejected could not be distinguished readily in an area where it is extremely difficult to make out the identity of the lavas themselves; rather one should search for the basement where the lavas show the minimum amount of deformation. The search for pre-Keewatin rocks is necessarily difficult in the region north of the Great Lakes where the volcanics have been heavily injected by two or more granite batholiths and so changed to gneisses, and hornblende, chlorite, and mica schists that their original structure and mineral

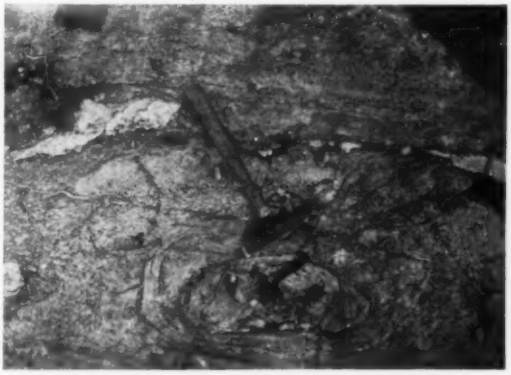

FIG. 1.—Photograph of a large lithophysa in the Keewatin lavas south of Lake Malartic. Vesicles in the lava appear as round pits showing practically no elongation due to deformation. The walls of the lithophysa are scarcely even fractured and close examination of the photograph will show that they have not been deformed to any noticeable extent.

composition are completely lost; this ancient series should be found more readily in that country, lying east of the gold and silver camps of northern Ontario and Quebec, where the pillow structures of the ancient lavas remain practically undeformed, and such minute structures as vesicles and fernlike growths, representing incipient crystallization in the lavas, stand out as striking characteristics with almost the same clearness as in any recent extrusive. Photographs of typical Keewatin volcanic rocks from the Harricana Basin are shown in Figures 1–3.

FIG. 2.—Volcanic tuff one mile south of Amos. The fragments are angular pieces of a vesicular rock of rhyolite composition. Many equidimensional angular fragments may be seen on the surface and show that the parallel arrangement of the fragments is not due to secondary deformation but to deposition of flat slabs of vesicular rhyolite upon the sides of a volcanic cone. Round amygdules and angular, rather than augen shaped, fragments show that secondary deformation and elongation parallel to the bedding has been negligible.

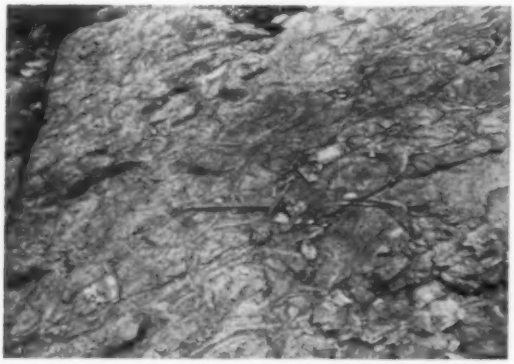

FIG. 3.—Pillow lavas on Lake de Montigny. Note that the flat sides of many of the pillows lie in the upper or north side of the picture. The flat side of the pillows is believed by Knight to correspond to the bottom of the lavas.

UPPER HARRICANA RIVER BASIN

The Keewatin volcanics in the Upper Harricana River Basin are only very slightly metamorphosed south of the Canadian National Railway which crosses the River at the town of Amos (Fig. 4);

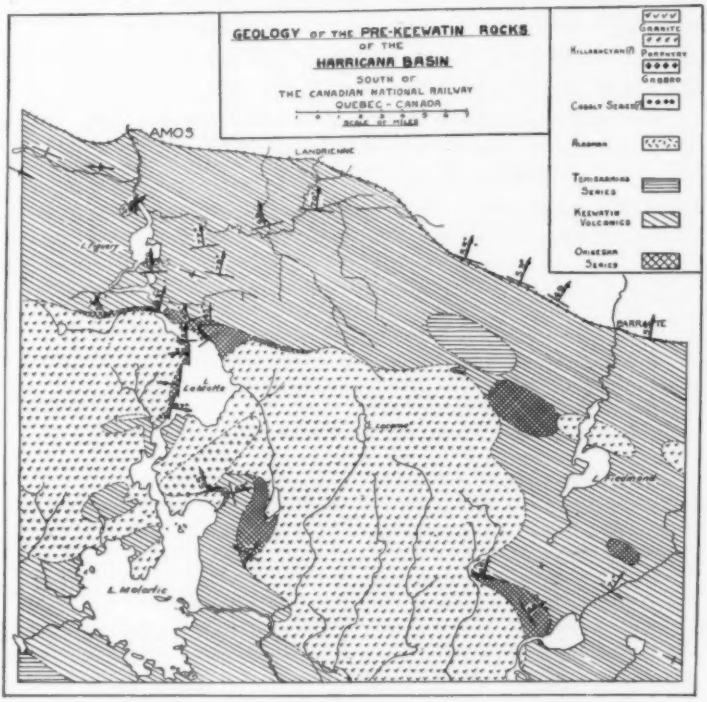

FIG. 4

from this place southward the volcanics become progressively more salic and carry a greater abundance of *ejectamenta* for about 1 mile, and, continuing southward even farther, become more femic and carry less volcanic tuff; in fact, these characteristics become even more pronounced than near the town itself. The Keewatin outcrops at various points near the river, and also back from it, as far south

as Lake la Motte (formerly called Okikeska). A nearly east-west ridge comes quite close to the river, on either side, and rocks are well exposed on points which jut out in the waterway. Careful examination showed that these were gneisses of greywacke composition and that they preserved a color-banding which was very persistent and due to primary differences in composition. This outcrop had been examined by Dr. J. A. Bancroft[1] and his assistants in 1912 and mapped by him as Temiskaming series.

The early work of Baron von Richthofen[2] and the more recent studies of other workers[3] have shown "that the rocks of a volcanic series become progressively, although somewhat irregularly, more salic from the base upwards."[4] Thus if Bancroft's classification of these sediments is correct, the Keewatin volcanics of this region show a reversal of the normal order of extrusion, which has been established for a great number of years. Whichever happens to be the case, the final data will be of very great scientific value. An extremely careful examination of the contact was made to determine the relative ages of the sedimentary and volcanic series.

STRUCTURAL RELATIONS OF THE GREYWACKE GNEISSES

The ridge of greywacke gneisses was followed eastward, and 2 miles from the river both the sedimentary and the volcanic series were found in contact along the steep south side of a hogback ridge (see Fig. 5). Dark femic basaltic flows, showing complete lack of pillow-structure and absence of volcanic tuffs, lay on the crest and on the north side of the hogback. At the west end of the ridge, slab-like inclusions of a black carbonaceous shale were found in the basal lava flows. Search of the south slope of the hogback revealed a

[1] *Mining Operations in the Province of Quebec, Quebec Department of Mines.*

[2] "The Natural System of Volcanic Rocks," *Calif. Acad. Sci. 1868*, Vol. I, Part II. pp. 29–35.

[3] J. P. Iddings, "Extrusive and Intrusive Rocks as Products of Magmatic Differentiation," *Quar. Jour. Geol. Soc., London*, Vol. LII, pp. 606–17; N. L. Bowen, "Later Stages in the Evolution of Igneous Rocks," *Jour. of Geol. Supplement*, Vol. XXIII, pp, 81–83, esp. p. 83.

[4] Basaltic flows may continue to be extruded to the very close of volcanic activity, but they are less common in the later stages. Rhyolitic lavas are lacking or very rare in the lower part of a volcanic series, whereas they make up the main part of the upper portion. Coarse tuffs are more commonly associated with rhyolitic than basaltic lavas.

finely laminated hornstone carrying abundant pyrite concretions which were very much more abundant along certain zones. This rock corresponds almost identically with a black carbonaceous slate described by Tanton[1] and found in the Harricana Basin north of the Canadian National Railway. The excellent exposure along the hogback enabled the author to observe the successive zones of what was formerly a black bituminous or carbonaceous shale—more

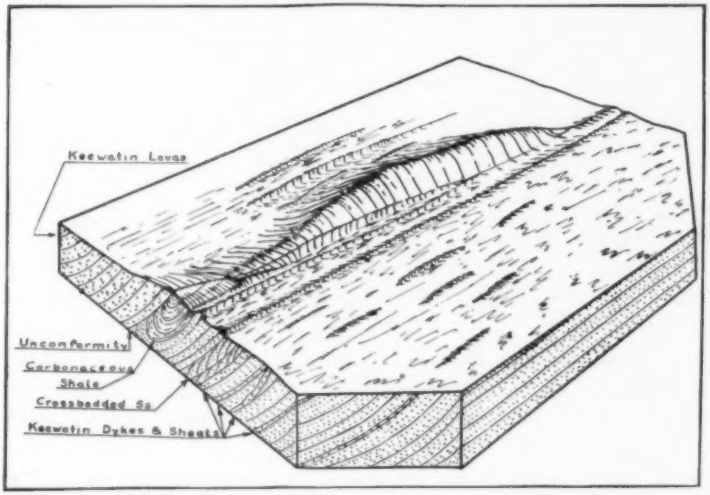

FIG. 5.—Block diagram showing the relations of the sediments to the Keewatin lavas and dykes as observed at the north end of Lake la Motte.

probably the former—passing beneath the lava flows. The structural relations are illustrated in Figure 5.

This observation seemed to indicate that the Keewatin was a normal volcanic series and went through the same succession of events as noted by Richthofen and that the sediments were not Temiskaming in age, but were really older than the Keewatin and served as a casting floor upon which the earliest basaltic lava streams poured out, picking up loose slabs and carrying the blocks along on their surface. If these sediments served as a floor on which the

[1] T. L. Tanton, *G.G.S., Mem. 109*, p. 30.

lavas poured out, dykes representing the conduits along which they rose, or sheets and dykes tributary to a neck from which they were extruded, should be found cutting these sediments. A great number of femic lamprophyre dykes cut the buff sandstones lying below the carbonaceous shale and are found between the hogback ridge and Lake la Motte, but none of these dykes were observed to cut lava flows more than a few feet above the base of the series. At one place a very much sheared granite dyke was in turn cut by the femic lamprophyre dykes or hypabyssal phase of the Keewatin volcanics.

The contact between the Keewatin and the sedimentary series was followed eastward 5 miles farther, and at different points very diverse rock types occurred at the contact. A silicated limestone lies $3\frac{1}{2}$ miles east of the Harricana River at the contact with the Keewatin. A greywacke quartzite, $2\frac{3}{4}$ miles east of this occurrence, lying at least 1,000 feet below the limestone member, is in contact with the basal lava flows.

The observations of the geological relationships of this band of sediments to the Keewatin volcanics lying to the north are therefore as follows:

1. Early workers in geology observed that the basal portion of any volcanic series is more femic than the upper portion. Also the upper portion carries more volcanic tuff beds than the lower. More recent studies have verified these earlier observations. The more femic and less tuffaceous part of the Keewatin volcanics is in contact with the sedimentary series.

2. Successively lower zones of the carbonaceous hornstone or slate pass beneath the Keewatin lava flows until finally the entire member is covered.

3. Different members of the sedimentary series are found in contact with the Keewatin lavas which indicate either lack of deposition or erosion after the beds were deposited. The fact that one of the members is a fine carbonaceous shale and another is a limestone indicates that the undulating contact is an erosion surface.

4. Femic lamprophyre dykes representing the hypabyssal phase of the Keewatin volcanics intrude the sedimentary series.

5. A granite intrusive into the sedimentary series is cut by the hypabyssal representatives of the Keewatin series.

6. Blocks of the sedimentary series are contained in the basal femic flows of the Keewatin volcanics.

STRATIGRAPHY

Two good sections of the sedimentary series can be obtained in the area east of the Harricana River. The first of these sections is north of Lake la Motte, 2 miles east of where the sediments were first found beside the river, and the second is $1\frac{3}{4}$ miles east of the above-mentioned section. The lithology of the rocks found in each of these sections differs considerably, and the presence of the limestone member in the easternmost section and its absence in the other would seem to indicate that the two sections belonged to different parts of the series. The limestone is believed to belong near the base of the series, because it is found far out from the central part of a syncline in the ancient series, and immediately overlies a very much metamorphosed gneissoid quartzite which is exposed at the extreme western part of the area, and also in the eastern part of the map of Lake Roy, about 7 miles west of Barraute, and at the second of the two sections mentioned above. The black carbonaceous shale has been found at only one place and that in the first of the two sections mentioned.

SECTION NORTH OF LAKE LA MOTTE

The thickness and lithology of the sediments in the first section taken from the Keewatin volcanics, 2 miles east of the Harricana River, south to Lake la Motte, are shown in Figure 6.

THE BLACK CARBONACEOUS SHALE

The black carbonaceous shale occurs in the axis of a syncline which passes beneath the Keewatin volcanics at the east end of the hogback ridge. The shale has been very highly lithified by contact metamorphism from the overlying lava; slaty cleavage although present, is poor and very coarse. Primary lamination in the rock is very fine and well developed; this lamination is accentuated by oxidation of pyrite and marcasite developed to different degrees along different zones. Concretions of iron sulphide up to an inch in diameter are very common; in some cases these concretions are pyrite while in others a "box" structure remains after the concretion has

weathered out, indicating that in some cases the sulphide may have been marcasite or marcasite changed to pyrite before weathering set in. When the rock is examined in thin section it is found to be unusually fine grained. "Shard" structure or other structures which might indicate that it is a volcanic ash are completely lacking. Small irregular black patches of carbonaceous matter are scattered abundantly through the rock. When the finely ground rock is ignited in a crucible, the carbonaceous matter is readily burned off, showing that the carbon has not yet changed to crystalline graphite.

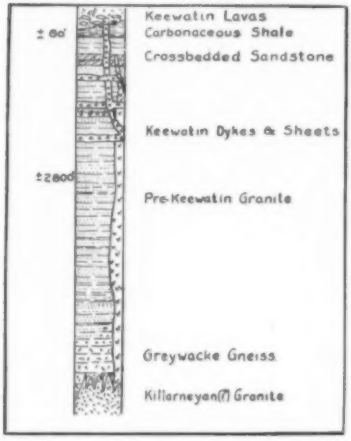

FIG. 6.—Columnar sections of the sediments at the north end of Lake la Motte.

The occurrence of carbonaceous matter disseminated through the rock in amorphous form indicates the presence of organic life in even these early rocks. (Crystalline graphite has been shown to have an inorganic origin in a number of cases, but hydrocarbons and amorphous carbon are generally believed to have been formed by the metamorphism of plant or animal matter.) The carbonaceous hornstone may have been formed by metamorphism from either a bituminous or carbonaceous shale. Concretions in a carbonaceous shale are usually siderite, and pyrite concretions are extremely rare. On the other hand, pyrite and marcasite concretions are quite common in bituminous shales. Although the original bituminous or carbonaceous nature of the sediments cannot be definitely settled, the preponderance of evidence seems to favor a bituminous origin for the carbonaceous matter. Bituminous matter suggests low forms of animal rather than plant life.

THE BUFF SANDSTONE MEMBER

The black shales are underlaid by a thick series of buff to greyish-brown impure sandstones, greywackes, and sandy shale with in-

jected femic sheets of Keewatin lava. About 100 feet below the black shale one or two cross-bedded layers occur in the sandstone series (see Fig. 7). The beds strike S.82°E. and dip 45°N.; the cross-bedding strikes NE. and dips about 57°NW. If these beds were restored to their horizontal position, the cross-bedding would strike NE. and dip approximately 15°NW. The sandstones appear to be continental sandstones, and the cross-bedding stream cross-bedding so that the clastic material must have been derived from the southeast, or up the dip of the cross-bedding.[1]

FIG. 7.—Photograph of a crossbedded layer of sandstone north of Lake la Motte. The outcrop of the bed is approximately parallel to the log lying in the depression left by the weathering out of a part of the bed.

INTRUSIVE ROCKS

The greywacke sandstone on the shore of Lake la Motte is highly injected by pegmatitic matter from the neighboring granite mass to the west, but the bedding can still be recognized by the color-banding in the rocks. Closer to the granite the sediments change to injected gneisses. The zone of gneiss is about 1,000 feet wide and grades into the intrusive granite.

A dyke of granite was found cutting the buff-colored sandstone

[1] Since this is a clastic series, whose fragmental material came from the direction of the Grenville limestone in southern Quebec and eastern Ontario, it could not be correlated with these ancient crystalline limestones. It is not the purpose of this paper to discuss the correlation of the Grenville, but on indirect evidence not yet published, it is the author's opinion that the clastic material was derived by the erosion of the Grenville gneisses.

north of Lake la Motte. This granite was in turn cut by the Keewatin dykes, proving that it belonged to the pre-Keewatin rocks of the region. The ancient sediments, therefore, are not only older than the Keewatin, but they were folded, intruded by granite, and eroded until representatives of this granite were nearly bared, before the period of Keewatin volcanism set in.

The granite dyke cuts across the sediments at an angle of about 15°. During folding of the sediments the dyke was sheared and developed a gneissic structure shown by the streaks of dark-brown biotite; although most of the mineral grains are highly granulated, a few larger ones remain; the margins of these grains are much granulated, but it is still possible to identify them as orthoclase crystals characterized by Carlsbad twins and as plagioclase feldspars having a composition Ab_9An_1 and showing both albite and baveno twinning. The quartz is granulated to a very much greater degree than the feldspars, and few of the original grains remain. The rock carries about a half of 1 per cent of apatite crystals. These crystals have a clear outer shell which surrounds a blue inner crystal showing very slight absorption. Fractures break some of the larger crystals into disjointed fragments and cross many of the smaller ones. The apatite seems to be a primary accessory mineral. Biotite and muscovite occur with their direction of elongation parallel to the plane of shearing, so that they are secondary in their present position. Whether they are primary minerals rearranged or are introduced minerals cannot be ascertained. The granulated character of some of the grains seems to indicate that they may be, in part, deformed primary minerals slightly reorganized.

A chemical analysis of the rock gave the following composition:

SiO_2	73.13
Al_2O_3	16.07
Fe_2O_3	0.04
FeO	0.96
CaO	2.11
MgO	0.43
K_2O	1.80
Na_2O	4.57
H_2O+	0.70
H_2O-	0.19
TiO_2	0.42
Total	100.42

Analyst, George W. Bain.

The rock carries 0.20 per cent P_2O_5, which in the analysis is recorded along with the Al_2O_3.

SECTION NORTHEAST OF LAKE LA MOTTE

The second section previously mentioned contains the remaining known members of the sedimentary series, and a columnar section for that portion is shown in Figure 8. It is unknown whether this section lies below or above that shown in Figure 6, but it is believed to lie below.

CONTINENTAL SANDSTONE MEMBER

About 70 feet of continental sandstone was found between the Keewatin volcanics and the actinolite rock of the sedimentary series at parts of the contact near which the second section was measured. This sandstone is buff colored and closely resembles the continental sandstone at the base of the section shown in Figure 6.

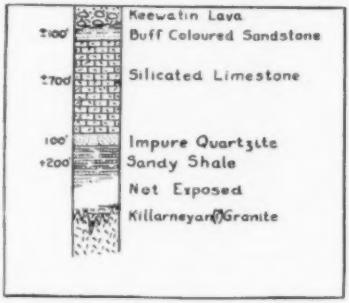

FIG. 8.—Columnar section of the sediments 3¾ miles east of the Harricana River.

THE LIMESTONE MEMBER

A limestone forms the second member of the series. This rock is very highly silicated and although some carbonate remains in all the specimens examined, actinolite and tremolite form the principal portion of the rock. Sheaflike masses of tremolite, so characteristic of silicated limestones, stand out very prominently on the weathered surface. Wilson[1] regarded a similar rock as being a hydrothermally altered igneous rock. However, examination of thin sections shows that the silicates have replaced the carbonate grains and that the replacing silicates have idiomorphic outlines, rather than etched outlines, which are characteristic of minerals in the process of being altered (Fig. 9). The carbonates have the granular habit and loosely interlocking margins characteristic of crystalline limestones. An inclusion of this rock found within 10 feet of the Keewatin contact and contained in one of the very early Keewatin dykes still remained,

[1] M. E. Wilson, *C.G.S., Mem. 39*, pp. 65–70.

for the most part, a crystalline dolomite. The occurrence of actinolite rock on Lake Roy shows shaly limestone bands still retained within it. (An actinolite rock closely resembling this one was found in the Keewatin lava. The matrix of the idiomorphic actinolite crystals, which had replaced a portion of the earlier rock, was uralite

FIG. 9.—Microphotograph showing actinolite needles which have replaced the crystalline dolomite. Ordinary light. Magnification 30 diameters. The actinolite needles pierce the carbonates and show no alteration effects within themselves. The rock is clearly due to silication of a carbonate rock rather than carbonatization of a silicate rock.

and chlorite, rather than carbonate. Brief examination of the hand specimens might lead one to believe that the rocks were the same and that the actinolite rock of the sedimentary series was a metamorphosed intrusive sill. Careful microscopic examination, however, revealed the foregoing outstanding differences which served to substantiate the sedimentary origin of the rock.)

THE QUARTZITE MEMBER

The actinolitized limestone is underlaid by a very impure, white, massive quartzite 100 feet thick. No bedding planes were observed in this member, and its contacts with the overlying and underlying beds were not exposed.

THE MICACEOUS SCHIST MEMBER

A crumbly micaceous schist in which the schistosity is parallel to the bedding underlies the quartzite. The rock was a buff sandy shale before metamorphism. Large blocks scale off parallel to the old bedding planes and give low, overhanging cliffs. This member of the series passes beneath a swamp which covers a large part of the area to the south.

OTHER OCCURRENCES OF PRE-KEEWATIN SEDIMENTS

The other outcrops of pre-Keewatin sediments in the Upper Harricana Basin are banded greywacke gneisses of which a typical outcrop much faulted is shown in Figure 10. They outcrop all along the west shore of Lake la Motte and again in two areas northeast of Lake Malartic. Three areas of greywacke gneisses occur near Lake Fiedmond. The area northwest from Lake Fiedmond has a few conglomerate bands at the northwestern end of the anticline.

SIMILAR ROCKS OBSERVED BY OTHERS

Tanton[1] found outcrops of black carbonaceous shale on Rest Lake and on the Octave River in the Harricana Basin north of the Canadian National Railway. The rock occurs as lenticular masses in the Keewatin lavas, and he regarded it as a finely stratified volcanic ash. It is hard to imagine how the amorphous carbon could have been deposited in with the Keewatin volcanic ash. Tanton states that the slate rock was rendered schistose by pressure. The carbonaceous slate might therefore have become involved in the volcanic series in two ways: first, it may have been squeezed into the lava series during deformation; or second, the lavas in which it was found might be the basal flows of the series and the carbonaceous

[1] *Op. cit.*, pp. 30–31.

slate might be present as slablike inclusions, similar to those at the occurrence described by the author.

Tanton[1] also describes ferruginous dolomites interbedded with slate from several localities in the Harricana Basin north of the Canadian National Railway. No mention is made of any development of actinolite or tremolite in this dolomite. The sediment is classed as part of the Keewatin iron formation.

FIG. 10.—Banded greywacke gneisses typical of the major portion of the sediments. An ordinary lead pencil serves as a scale.

SUMMARY AND CONCLUSIONS

1. The sedimentary series consists of carbonaceous slate, continental sandstone, limestone, quartzite, and greywacke gneiss, in which the original bedding can still be recognized by variation in color and character of the clastic material.

2. The sediments are intruded by a granite which is in turn intruded by Keewatin femic dykes and sheets.

3. The sediments are overlaid unconformably by femic lava flows of Keewatin age.

4. Different members of the sedimentary series lie in contact with the basal lavas of the Keewatin.

[1] *Op. cit.*, pp. 31–36.

5. Cross-bedding seems to indicate that the clastic material forming the sandstones comes from the southeast.

6. The presence of carbonaceous matter in the slates seems to indicate that organic life was present at as early a period as the formation of these rocks.

7. Four independent lines of reasoning agree in showing that the sediments are older than the Keewatin: (*a*) blocks of sediments are included in the basal lava flows; (*b*) the sediments are adjacent to the femic portion of the volcanic series and are not faulted into that position; (*c*) the lavas lie upon an erosion surface developed across the folded sediments; (*d*) the Keewatin dykes intrude the sedimentary series.

8. For this pre-Keewatin series of rocks, the author proposes the name Okikeska series, after the old name of the lake around which they are best developed.

A NOTE ON RHIZOCRETIONS[1]

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Geological Survey of Canada, Ottawa

ABSTRACT

The paper describes the occurrence of concretions of lime and sand which were found inclosing living roots. The suggestion is made that the presence of certain bacteria, or of fungi, on the living roots may constitute the initial factor in the development of root concretions.

The small cylindrical concretions composed of calcium carbonate and quartz sand, which occur in abundance at certain localities in the superficial beds of Pleistocene sands in Ontario, have been previously described by the writer while indicating the distinctive features of the different types of Quaternary rhizocretions or root-shaped concretions known to him.[2] These concretions usually show the remains of a decayed root, or the tubular cavity left by it, traversing the central or axial part of the concretion. Until recently the writer had assumed, because he had found only decayed roots in them, that these concretions developed after the death of the roots, and represented a phase of lithification co-ordinate with root decay under special conditions. Lately, however, in the sand pits near Rideau Junction, Ontario, examples of these concretions have been found which were traversed by living roots. Some, and probably all, rhizocretions must therefore be recognized as phenomena associated with the growth, instead of the decay, of roots. This new information connecting the formation of root concretions with root growth limits their period of development to the lifetime of the tree with which they are associated. The root concretions here figured inclose birch roots which were living when found at the sand pits near Rideau Junction, Ontario, and are rather larger than most of the rhizocretions which have been observed inclosing the decayed remains of small roots. It therefore appears that root concretions reach their complete size development during the lifetime

[1] Published with the permission of the Director, Geological Survey of Canada, Ottawa.

[2] "Range and Distribution of Certain Types of Canadian Pleistocene Concretions," *Bull. Geol. Soc. Amer.*, Vol. XXXIV (1923), p. 629, Fig. 3, Pl. II.

of the roots about which they form. The sands in which the Rideau Junction rhizocretions occur are marine sands in which Pleistocene marine shells are present at various levels, though not particularly abundant. The marine shells in the sand from which percolating waters could draw lime are probably the source of the calcium carbonate in the rhizocretions. Examination with a hand lens of the lime-cemented mass of sand comprising the lithified investments of the roots shows them to be intimately penetrated by innumerable tiny rootlets, many of which are of microscopic size. It thus appears

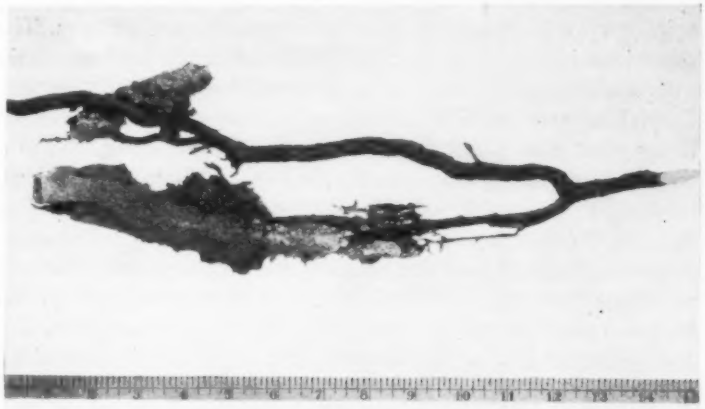

FIG. 1.—Birch roots encased while living in lime-cemented sand concretions (*rhizocretions*).

that the formation of these structures was intimately connected with the growth activities of the smallest roots.

On a priori grounds it might be inferred that the essential conditions for the production of these concretions would be furnished by a stratum of marl overlying a bed of sand. But at McKay Lake, near Ottawa, where a bed of fossil marl directly overlies a deposit of sand, and where innumerable roots may be seen in sand-pit excavations penetrating both deposits, careful search has failed to discover a single root concretion. Since these calcareous root-enveloping structures are in no way connected with marl beds associated with sand where examined, some conditions other than a superabundance of calcium carbonate appear to be required to produce them.

It is the writer's belief that these conditions include symbiotic relations between the roots and certain bacteria or fungi which, through their normal activities, cause the precipitation on the roots to which they are attached of calcium carbonate from the water transpired by the tree. The precipitation of certain iron compounds and some other minerals by bacteria is a familiar fact. In addition, the extraordinary abundance of bacteria in ordinary soils is indicated by K. F. Kellerman's estimate of 15,000,000 to 300,000,000 individuals in each ounce of fertile soil.

Fungi may also be regarded as a hypothetical, and in the writer's opinion a probable, factor in the formation of these structures. The condition of mycorrhiza may lead to their formation when certain species of fungi and favorable physical conditions are in conjunction. Careful examination of the conditions where concretions enveloping living roots were found show that only in certain areas, and in a small proportion of the numerous roots penetrating the sand in such areas, do they become incrusted with the lithified sand. Dr. Robert Paulson,[1] in speaking of the white birch, states: "Should there be an accumulation of decaying leaves at, or near, the foot of the tree, numerous thread-like rootlets, each infected with mycorrhiza, will be found ramifying throughout the decaying mass.[2] Paulson, who has recently figured a specimen of birch root showing its altered appearance resulting from association with a mycorrhizal fungus, states[3] "Three to four states of mycorrhiza, differing in form, size, texture, and color, occur on the same species of tree, and quite frequently two forms appear on an identical root-branch." Some form or association of fungi not yet recognized by botanists may be responsible for the class of structures described in this paper.

Whatever the exact biochemical factors concerned in the growth of these structures may be, the present observation indicates that their activity is coincident with the growth of the tree about whose roots the concretions form.

[1] A letter received from Dr. Paulson since this manuscript was written states that he has seen a concretion collected, apparently, from the Landgate beds at Folkstone, England, which is similar to those occurring at the Rideau Junction sand pits.

[2] "Birch Groves of Epping Forest," *The Essex Naturalist*, Vol. XX, Part II (1922), pp. 69–85.

[3] "Tree Mycorrhiza," *Trans. British Mycological Soc.*, Vol. IX. Part IV (August, 1924), p. 215.

THE SPOKANE FLOOD: A DISCUSSION

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State College of Washington, Pullman, Wash.

The interpretation which Bretz[1] gives to sand and gravel beds found at the mouth of the Tucannon River, below Riparia, on the Snake River, Washington, seems to me very plausible, indeed. I examined these sand deposits for the state of Washington, before the "Channeled Scabland" idea was published, and at that time came to the conclusion that the river had been dammed.

The condition, as Bretz pictures it, is a lake about 250 feet deep at Riparia and 50 feet deep at Lewiston. I am inclined to believe that this lake was deeper. At Lewiston and at Clarkston there are gravel terraces over 100 feet above the Snake River which extend to the floor of the canyon. These seem to correspond to the Riparia dam. Above Lewiston and Clarkston are terraces at about 200 and 400 feet above the river. The highest of these may represent the delta of the Snake as it entered this lake, for its altitude is about that of the Wallula Gateway ponding. At Wawawai, 30 miles down the river from Lewiston and 50 feet lower in elevation, is a terrace lying 100 feet above the river. At Central Ferry, much the same condition exists. The gravels of these terraces are composed largely of well-rounded granite, porphyry, and metamorphic rocks washed from the Idaho mountains.

A much higher series of terrace gravel, sand, and pumice deposits occur along the Snake River from Wawawai to Lewiston. The Lewiston orchards are located on a terrace over 600 feet above the river, at least 1,300 A.T. At Wawawai, terrace deposits of sand, gravel, as well as very large bowlders of granite, occur at least 500 feet above the river, or 1,150 feet A.T.; and pumice-dust terraces lie even higher, running up to about 1,500 feet A.T. These deposits in places can be traced, more or less satisfactorily, all the way down to

[1] J Harlen Bretz, "The Spokane Flood Beyond the Channeled Scablands," *Jour. Geol.*, Vol. XXXIII (1925), pp. 97–115.

the lower terrace. They occur within the steep tributary canyons where they probably would have been completely destroyed had they been formed during the original canyon cutting. They seem to me to belong to the damming episode of the Wallula Gateway, which I think must have occurred previous to the building of the Riparia dam, because the Riparia delta, though far upstream, is much lower than the Wallula ponding.

It seems to me that there is evidence enough to indicate that these two river-lakes (of two episodes) were each filled with sediment and then each flushed out. After the higher filling of the river channel, which occurred during the damming at the Wallula Gateway, the lake thus formed must have been almost completely flushed out before the Riparia dam was formed.

The lower slopes of the Snake River canyon at Wawawai are noticeably steeper than the upper and are nearly free from talus. This break in topography may represent a second cycle of erosion, antedating the Spokane flood. The removal of the talus probably occurred during the flush, which followed the breaking of the Riparia dam.

There is one question, which, when answered, may throw some more light on the whole situation. Should not both the Snake and Clearwater rivers have borne floods during the time of the melting of the Spokane ice, for the great Rocky Mountain glaciers were melting and feeding water into these streams? The occurrence of large bowlders of granite in the high terraces suggests the presence of floating bergs.

REVIEWS

Coal and Civilization. By E. C. JEFFREY. New York: Macmillan Co., 1925. Pp. 178, figs. 44. $2.50.

The title of this little book is really a misnomer. It might lead one to expect a treatise in economics, with strong historical and geographic leanings, but instead, the reader finds that the structure, general organization, and origin of the various kinds of coal are the topics most trenchantly treated. From the geologist's viewpoint this is fortunate, since the material and conclusions presented are largely the fruits of new methods of investigation devised by the author, and as such are instructive and valuable.

The brief opening chapter on coal and civilization, which gives its name to the book, is snappy and interesting, but seemingly overdrawn. The author endeavors to demonstrate that our age is an age of coal, and that surprisingly many of the leading political problems of the world are either at present connected with coal supplies or will be ultimately.

There are then taken up, in order, the manner of preservation of the organic matter to become coal, the special structural and constitutional characteristics of the different kinds of coal, and finally the origin and uses of these coals. An intensive microscopic study of the structures revealed in thin sections of coal affords most of the basis for this; little consideration is given to other lines of investigation.

The main thesis is that the organic matter of the coal has been deposited under water in lakes and lagoons, and that the vast majority of it has been transported to its place of accumulation by the water of the lakes, together with winds and running water from the surrounding land.

Evidence cited in support of this conclusion is (1) the manner in which ponds and lakes are now being gradually filled with organic muck; (2) the great abundance of spores in the coal; (3) the presence of fragments of charcoal in the coal, which suggest forest fires outside the borders of the lake; and (4) the remarkable state of preservation of the structures brought out by the microscope. The *in situ* hypothesis for the origin of coal, widely prevalent today, is dismissed cavalierly without much dis-

cussion. Nothing is said of the elaborate microscopic investigations of Thiessen, and little of the geological aspects of the problem.

Wherever the trees grew, they of course might be set afire by lightning and produce charcoal. Whether the accumulated organic matter in a bog close by would also be consumed in part would depend upon the amount of water present. The amount of standing water postulated for the basin of accumulation is, of course, one of the chief differences between the two hypotheses. Spores might seemingly collect in either a marsh or open lake.

One of the chief problems connected with the origin of coal is the surprising purity of the coal in many cases. As found in the field, seams of remarkably pure coal are interstratified with tens or scores of feet of shale and sandstone. The transitions are sharp. One may well wonder, in the first place, if the coal material was washed into lakes from surrounding lands, how it is possible that an almost negligible amount of mud and sand accompanied it. And then it is to be explained how, beginning abruptly, scores, and in some cases hundreds, of feet of mud and sand were deposited over the organic layer, to be followed again by another seam of coal relatively free from outside mineral matter. The conditions producing these changes prevailed at the same time over areas of several thousand square miles. They may perhaps be explained on the transportation hypothesis, but they cannot well be ignored.

Oil rocks and cannel coal, according to Jeffrey, are closely related, their components being laid down in tranquil water, and consisting to a predominating degree of spores. Coking coals have been derived largely from woody material; they have reached the proper degree of carbonification, but, on the other hand, they have not gone too far. Coal is spoken of in several places as a mineral.

The treatment is one-sided and dogmatic. The author manifests a contemptuous tone toward views of others which, in itself, naturally engenders antagonism and disrespect. Perhaps this is partly the result of this attempt to treat a tremendous subject, having many different phases, in such brief space. Nevertheless, in the later pages, frequent repetitions are allowed to consume valuable space.

In the opinion of the reviewer, the author has contributed a great deal to the subject of coal in this extremely readable and well-illustrated book. But just how far he is to be followed in his conclusions is not so easy to say.

R. T. C.

Movement of Continental Masses under Action of Tidal Forces. By FRANK BURSLEY TAYLOR, Pan-American Geologist, February, 1925. Pp. 15–50, pl. and figs.

There are two reasons why I should prepare a review of this paper. One of these is that the maps put forward to show the form and distribution of the mountain arcs, which of course must determine the conclusions based upon them, do not accord with reality or with the views which were put forth by Suess. The second reason is that in this article I am accused of doing the great master "a serious injustice" through "representing him as teaching an impossible doctrine."

I cannot rest under this charge without a reply. It was my good fortune to know the elder Suess more intimately, perhaps, than any other American geologist. To know him was to love him, and of course also to greatly admire him for his exceptional gifts of mind and heart. I have also been put under obligation to him for much kindly consideration, and it was he who wrote the Introduction to my monograph on *Some Principles of Seismic Geology*. I was last in his home when the shadows of approaching dissolution were already closing in about him, but without in the least altering his cheerful and kindly nature.

My active advocacy of the larger Suessian principles began, I believe, before any American geologist had expressed approval of them. My support of these views was made prominent in published writings, and for a number of years I conducted a seminary in the reading of *The Face of the Earth*. Notwithstanding all this, it has not seemed to me to be presumptious to point out wherein I believe certain of the Suess conclusions to be in error, and I have not hesitated to do this in the *Journal of Geology*, in my "Earth Evolution and Its Facial Expression," and elsewhere.

But to come to the specific charge against me. The difficulty which I find in making the surface crustal earth layers flow southward into the sack of compressed arcs over the Malaysian extension of the Asiatic continent would be at once apparent if Taylor had not conveniently to his purpose omitted from his map the arcs of Farther India which produce in this region a veritable bottle-neck to the sack. Taylor's tendency to distort or choose from the arcs for his purpose is noticeable over a large part of his map. Examine, for example, his world-map (Fig. 1). If the arcs of Asia have been pushed up by movement toward the south, as is indicated by his arrows (and here he is in accord with Suess), by the same token the Alps and Carpathians were formed by a northward push, as Suess and everyone else except Taylor, who has assumed a push from the rear, has represented them. Yet the arrow near the Alps on Taylor's

map points southward, just as do those in Asia; and so of course, according to Taylor, there is evidence in the Alps and Carpathians of a slide toward the Equator. Again, the Betic Cordillera surrounding the Straits of Gibraltar represents, on the assumption made, an outward movement toward all sides but the east, but Taylor supplies on his map a single arrow pointing to the south.

Within the Southern Hemisphere the one dominating mountain range of folded rocks is, of course, the great Andean system, which trends along a meridian and must therefore represent a slide either toward the east or the west—certainly not toward the north, as Taylor represents it. The West Indian arcs are—in the Suessian sense, of course—due to outthrusts from the interior region; toward the north in the Greater Antilles, to the east in the Lesser Antilles, and to the south in a part of the east and west ranges of the north coast of South America. Taylor supplies in this region arrows which point only in the way his theory requires them to point. He goes so far in this region as to represent three completely closed and outwardly convex areas, which on his own assumption would require deep holes to develop toward the center of each area.

In summary, the Taylor maps and the conclusions based upon them do violence to the facts as they were so laboriously assembled and discussed by Suess.

WILLIAM HERBERT HOBBS

Transactions and Proceedings of the New Zealand Institute, Volume LV. By W. A. G. SKINNER. London: Government Printing Office, Wheldon, Wesley & Son, 28 Essex St., Strand, 1924.

Among twenty-four geological papers contained in this volume is one by W. N. Benson entitled "The Structural Features of the Margin of Australasia" which discusses the tectonic features and later geological history of this zone in an attempt to throw new light on the structure and history of New Zealand. The author has presented a definite and unified conception of the tectonics operative in Australasia.

Another paper worthy of note is "The Post-Tertiary History of New Zealand," by J. Henderson, which deals chiefly with changes in the height of the land with respect to sea-level. The other articles are mostly of a paleontologic nature and of local interest.

L. F. A.

The Pleistocene of the Middle Region of North America and Its Vertebrate Remains. By OLIVER P. HAY. Washington: Carnegie Institution Publication No. 322A., 1924. Pp. 385. $2.50.

A continuation of Hay's valuable summary of the Pleistocene vertebrate fauna of America. In the first volume the territory east of the Mississippi was covered; in the present, the territory to the Rockies. The first two-thirds of the volume give a systematic account of the finds of the larger Mammalia, the final portion a summary by states.

A. S. R.

Triassic Fishes from Spitzbergen. By ERIK A:SON STENSIO. Part I. Vienna: Adolf Holzhausen, 1921. Pp. 302, pls. 35. Part II. Stockholm: Kungl. Svenska Vetenskapsakademiens Handlingar. 3 Ser., Band 2, No. 1, 1925. Pp. 261, pls. 34.

This work is of a vastly broader nature than its title would indicate. Besides a systematic account of the Spitzbergen fish, the morphology of the forms considered is thoroughly investigated, and much is added to our knowledge of the mutual relations and skeletal evolution of the bony fish.

Part I treats especially of the coelacanths and the lower Actinopterygii, especially the palaeoniscids. Part II is mainly devoted to the problematical genus *Saurichthys*, which Stensio places in the "Chrondrostei," with the "sturgeons" (in a broad sense) as the nearest relatives.

This is, without question, the most important recent work on fossil fish. The publication of Stensio's work on the Devonian forms will be awaited with interest.

A. S. R.

Jungtertiare Carnivoren Chinas. By OTTO ZDANSKY. Peking: Palaeontologia Sinica, Ser. C, Vol. II, fasc. 1., 1924. Pp. 149, pls. 33.

Some thirty-eight species of fossil carnivores are described from Northern China, mostly from the Hipparion beds, which the author believes from the evidence obtained to be Upper Miocene. In the Canidae, a Simocyon close to the European form is described, as well as two species of Canis and (?)Vulpes. The Ursidae include a good dentition of Indarctos, otherwise known only from Indian and American fragments. Several new genera and a number of species of mustelids are described, and the classification of the group discussed. Hyaena is abundant, as well as Ictitherium. Of the felids, the finds include two new genera, Metailurus

(which includes North American species of Pseudailurus) and the large Dinofelis.

Between Swedish co-operation with the Chinese Survey (of which this volume is a product) and the expeditions of the American Museum, our knowledge of the vertebrate paleontology of Eastern Asia is increasing with gratifying rapidity.

A. S. R.

Mineral and Grant Counties. By DAVID B. REGER and R. C. TUCKER. Morgantown: West Virginia Geological Survey, 1924. Pp. 812, pls. 43, figs. 31, maps 4.

This volume gives a very detailed account of the geology of Mineral and Grant counties in northeastern West Virginia. Many coal analyses, well logs, and geologic sections are included, as well as an Appendix on "Levels." R. S. Lull contributes an article on "Reptilian Footprints from the Carboniferous of the Area." This is an excellent reference work.

J. H. HUGHES

The Geology of the Silverwood–Lucky Valley Area. By H. C. RICHARDS and W. H. BRYAN. "Proceedings of the Royal Society of Queensland," Vol. XXXVI, No. 6, 1924. Pp. 107, pls. 13, map. 1, secs. 2, block diagram 1.

This area in southeastern Queensland contains folded and faulted Devonian andesitic lavas and tuffs, radiolarian cherts and cherty shales, Permo-carboniferous tuffs and flows, Permian granite, and Jurassic shales and sandstones.

The geology is excellently presented but is chiefly of local interest.

L. F. A.

Geology along the Blackstone, Brazeau and Pembrina Rivers in the Foothills Belt, Alberta. By J. A. ALLAN and R. L. RUTHERFORD. Edmonton: University of Alberta. Pp. 53, pls. 6, maps 1.

The geology of this region involves three groups of Cretaceous strata, the Kootenay and Montana continental deposits, and the intervening marine strata of the Colorado group. These are folded and faulted into structures characteristic of the foothill belt. The Kootenay and Saunders (Montana) formations contain commercial quantities of coal.

L. F. A.